(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 0 807 911 A2

(12) EUROPEAN PATENT APPLICATION

(43) Date of publication:
19.11.1997 Bulletin 1997/47

(51) Int Cl.6: G07F 19/00, G06F 17/60, H04L 9/32

(21) Application number: 97303229.5

(22) Date of filing: 12.05.1997

(84) Designated Contracting States:
AT BE CH DE DK ES FI FR GB GR IE IT LI LU MC NL PT SE
Designated Extension States:
AL LT LV RO SI

(30) Priority: 15.05.1996 US 648442
21.04.1997 US 845196

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(54) Client/server protocol for proving authenticity

(57) A protocol for establishing the authenticity of a client to a server in an electronic transaction by encrypting a certificate with a key known only to the client and the server. The trust of the server, if necessary, can be established by a public key protocol. The client generates and sends over a communications channel a message containing at least a part of a certificate encrypted with the server's public key or a secret session key. The server receives and processes the message to recover at least part of the certificate, verifies and accepts it as proof of the client's authenticity.

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Description

The invention relates to a protocol for one party to an electronic transaction, as for example a client in a client-server transaction, to prove its authenticity to the other party of the transaction.

BACKGROUND OF THE INVENTION

Client-server systems provide electronic access by the client to data, information, accounts and other material stored at the server. In financial transactions, the system provides a client electronic access to accounts and financial resources.

In a client-server transaction, the client is required to prove to the server that it is an authentic client, and not some impersonator or other unauthorized party. Protocols are known by which a client proves to a server its authenticity, while at the same time it does not reveal information that could be misused by a third party.

A standard well known protocol for proving authenticity involves public-key cryptography. The client establishes a public key/private key pair and provides the public key to the server. In a transaction, to prove its authenticity to the server, the client forms a digital signature with its private key on a time-varying message, and the server verifies the digital signature with the client's public key. The time-varying message, which may be a timestamp or a challenge supplied by the server, is different in each instance. This message, when checked by the server, provides safeguards against a third party impersonating the client by simply replaying copies of previous signatures of the client that the third party has intercepted or otherwise acquired.

In the standard protocol described above, the server trusts that the public key belongs to the client, i.e., that the client is in fact actively involved in the transaction because it is presumed that only the client knows the private key and can form valid digital signatures. A convenient way to establish trust in a public key is to use a certificate. This is accomplished by a certification authority issuing public-key certificates signed with the certification authority's private key, which thereby asserts to the server that the client's public key is a valid public key issued by or registered with the certification authority. Assuming the server trusts the certification authority's public key, then it trusts the client's certificate, the client's public key and ultimately the client's authenticity.

With typical public-key cryptosystems, it is computationally expensive to form digital signatures because of the need to perform an exponentiation operation. In some electronic transactions, for example, those involving a smart card client where the computational capacity is limited, the standard protocol using a digital signature is computationally expensive and is therefore a significant burden.

Beller and Yacobi, in an article entitled "Fully-Fledged Two-Way Public Key Authentication and Key Agreement for Low-Cost Terminals" *ELECTRONICS LETTERS*, May 27, 1993, Vol. 29, No. 11, at pages 999-1000, describe a protocol that provides for less on-line computation on one side of the protocol. In this protocol authentication of the server by the client is carried out by the server sending a random challenge with an expected "colour", structure or format, to the client for verification by the client. Authentication of the client by the server is achieved by the client sending to the server its identity, public key, certificate and a signature on the random challenge for verification of the certificate and the signature by the server. The protocol is described as being useful where one side of the interaction is a low-cost customer device such as portable telephones, home banking terminals, smart cards and notebook computers.

Other protocols are known for establishing the authenticity of a client to a server. Client authentication protocols such as those based on secret-key cryptography exist, but often have the limitation that the server must be on-line, or the server must store a key which can be used to impersonate arbitrary clients. In Cellular Digital Packet Data systems, a client authenticates itself to a server by sending a one time password encrypted with a Diffie-Hellman shared key, and the server returns a new password for the next session. Again, the server must be on-line or the client must share a different password with each server, which can be inconvenient.

BRIEF DESCRIPTION OF THE INVENTION

A protocol that is less computationally expensive for a client but achieves similar goals as the standard protocol is used to develop a server's trust in the client. In this protocol, a certificate provided by a trusted certification authority to the client is encrypted with a key known only to the client and the server or the public key of the server. The client forms no digital signature. Since only the client and the server it trusts have access to the certificate, the certificate itself is proof of the authenticity of the client. This protocol is particularly useful in client devices having small computational capacity, e.g., a smart card.

Additional interactive protocols are disclosed whereby messages are exchanged between client and server to establish authenticity of both the client and the server as well as protocols wherein only a portion of the client's certificate is encrypted. Moreover, the certificate can include a one way function, such as a cryptographic hash function of a secret value or a root of a hash tree of secret values for protection against the certification authority or unauthorized servers, respectively.

A still further more general protocol involves a user, which may be an individual, a computer or some other entity, connected to a verifier by way of an encrypted communications channel such that the user can confidentially deliver to the verifier information essential to verify the message.

DESCRIPTION OF THE DRAWINGS

Figure 1 schematically illustrates the components of a smart card;

Figure 2 illustrates the components of a server;

Figure 3A is a flow diagram showing the procedure for generating messages by a client to prove its authenticity to a server;

Figure 3B is a flow diagram showing the processing at the server of messages sent by a client to authenticate the client;

Figure 4A is a flow diagram illustrating an interactive embodiment of the invention where the server sends a copy of its certificate to a client;

Figure 4B is a flow diagram illustrating an interactive embodiment of the invention where the server sends a copy of its certificate and a time-varying value to the client;

Figure 4C is a flow diagram illustrating an interactive embodiment of the invention where the server sends a time-varying value to the client;

Figure 5 is a flow diagram illustrating an interactive embodiment of the invention where a client is sent a message signed by the server;

Figure 6 is a partial flow diagram illustrating a variation in the messages generated by the client;

Figure 7 is a partial flow diagram illustrating a version of the invention where a client's certificate is sent directly to a server;

Figure 8 is a partial flow diagram of Figure 5 modified so that only part of the client's certificate is encrypted;

Figure 9 is a partial flow diagram of Figure 6 modified so that only part of the client's certificate is encrypted;

Figure 10 is a partial flow diagram of Figure 7 modified so that only part of the client's certificate is encrypted;

Figure 11 is an illustration of a hash tree which may be used to prevent misuse by a server; and

Figure 12 illustrates a still further flow diagram of essential elements of a system having a more general protocol but which may have features of other embodiments disclosed herein added thereto.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The specific description of the invention is set forth in the environment of a smart card client. However, the invention is not limited to a smart card client since the disclosed protocols are applicable to client/server systems in general, and in particular clients having low computational capacity such as portable telephones, notebook computers and home banking terminals. In an even more general manner the disclosed exemplary embodiments as described later can involve a user, which can be an individual, a computer or some other entity, which is connected to a verifier, which can be a client, a server or some other entity, via an encrypted communications channel whereby the user can confidentially deliver to the verifier information essential to verify the message.

A smart card includes a microchip containing a processor and memories to hold programs and data. Figure 1 illustrates a smart card 1 comprising a processor 2, an erasable programmable read only memory (EPROM) 3, programmable read only memory (PROM) 4, random access memory (RAM) 5, input/output (I/O) port 6, number generator 7, clock 8 and power source 9. PROM 4 holds the card operating system and RAM 5 holds temporary results of calculations. EPROM 3 holds the certificate for the card. This certificate for the card, unlike the usual public key certificate, need not include the public key of the client since authentication of the client by the server does not rely on the public key of the client. A cache of public keys of one or more servers may also be stored in PROM 4 or EPROM 3. Number generator 7 provides random seed numbers to the processor for generating secret session keys. Clock 8, conventional and well known in the art, is used for generating a timestamp and for verifying a received timestamp. Clock 8 is optional where the server's timestamp or time-varying value is used by the client to provide a time-varying value or where a challenge procedure is followed. Power source 9 is a battery when a card has a clock. Otherwise, power may be supplied by an external source or a server. I/O terminals 6 provide a means for external communications.

The public key of a trusted certification authority may be stored in PROM 4 or EPROM 3. PROM 4, or the RAM 5 if non-volatile, may have a section for storing certificate revocation lists (CRLs). Such a list would include a list of servers whose certificates have expired or been revoked. This list would be provided by signed and dated messages from the trusted certification authority either directly or indirectly while in a communicating relationship with a server. Reference to the list during the initial stages of the protocol will indicate whether the transaction being initiated is with a valid server or with one holding a revoked certificate, and thereby whether a received server's certificate is to be verified.

The card manufacturer initializes the smart card us-

ing conventional techniques. PROM 4 is loaded with an operating program to be executed by processor 2, clock 8 is set (or an initial time-varying value, e.g., a sequence number or a timestamp is set in one of the memories when a clock is not used) and the certificate associated with the card and the trusted certification authority's public key are loaded into the memories. Optionally, server public keys and CRLs are also loaded into the memories.

A server 40 as illustrated in Figure 2 includes a processor 60, a facility for generating a time-varying value or timestamp 42, input/output port 63, and a memory 61 for holding the operating program for the processor, the private key $PRIV_{SERV}$ associated with the server's public key PUB_{SERV} and the public key PUB_{TCA} of the trusted certification authority that signed the client's certificate. In addition, memory 61 may hold a certificate revocation list (CRL) and a certificate (CERT-S) for its public key. The facility for generating a time-varying value 42 may comprise a clock for generating a timestamp or other means for generating a time-varying value. The I/O port 63 provides an interface between the processor of the server and external entities.

Figure 3A illustrates the processing by a client for generating and sending messages to a server for use by the server to prove the client's authenticity. A client at 101 generates or provides a time-varying value (TS). This may be a timestamp or other value which changes with time. The client also generates a random secret session key (KSS) at 102 employing a number generator or other means to provide a random seed number. At step 103, the time-varying value TS and the secret session key KSS are concatenated and at 104 the result is encrypted with the server's public key PUB_{SERV} which has been retrieved from memory 4 or 5. The encrypted message $\{KSS|TS\}PUB_{SERV}$ is sent to the server at 107. The client's certificate (CERT-C) is retrieved from memory, EPROM 3, at 105, encrypted with the secret session key KSS at 106 to form message {CERT-C}kSS which is sent to the server at 108. The sending operations 107 and 108 may be combined into one operation.

Figure 3B illustrates the processing at a server 40 of messages received from a client via I/O port 63 for the purpose of ensuring the authenticity of the client. Initially, the server decrypts at 201 the message $\{KSS(TS) PUB_{SERV}$ using its private key $PRIV_{SERV}$ recovered from memory 61. At 202 the received time-varying value TS is compared with a reference value obtained from the server's facility for generating a time-varying value 42. Where the values do not compare an error signal is generated at 207 and the process is terminated. Where the time-varying values compare, the processing continues at 203 with recovery of the secret session key KSS and at 204 by decrypting of the message {CERT-C}KSS using the secret session key. This provides the server with the client's certificate (CERT-C) which is then at 205 subjected to a public key operation using the trusted certification authority's public key PUB_{TCA} retrieved from memory 61. At 206 a verification of the certificate (CERT-C) is performed with the subsequent generation at 208 of an error signal where the certificate cannot be verified or the generating of an authentic signal at 209 where the certificate is found to be authentic. The verification procedure at 206 may include the use of the CRL stored in memory 61.

One embodiment of the invention is a non-interactive version where the protocol requires only the sending of messages over a communications channel by a client to the server with which it is seeking to execute a transaction. In other interactive embodiments (Figures 4A, 4B and 4C), a message, designated 11 in the drawing figures, containing information needed by the client to produce authenticating messages for the server, e.g., the public key of the server and/or a time-varying value provided by the server, is sent by the server to the client. In a further interactive embodiment (Figure 5), the client has need of assurance of the server's presence in the transaction and therefore requires a message signed by the server. Figure 6 represents a modification of the embodiments of the invention due to the message generated by the client having the time-varying value combined with the certificate of the client. Figure 7 shows a version of the invention where a session key is not used. Moreover, Figures 8 to 10 illustrate modifications to the embodiments of Figures 5 to 7 wherein only a part of the client's certificate is encrypted. Additionally, Figure 12 illustrates a fundamental protocol whereby a user can confidentially deliver to a verifier information which is essential to verify a message signed by a credential issuing authority, but which may be modified to include one or more features of other disclosed embodiments.

In the non-interactive embodiment, there is no message 11 sent from server 40 to a client in the authentication protocol. The protocol is essentially as shown in Figures 3A and 3B with a client configuration as in Figure 1 and a server configuration as in Figure 2. The client upon gaining access to a server 40 obtains the server's public key from a local storage, generates a random secret session key KSS (102), concatenates (103) it with an internally generated time-varying value, encrypts (104) the result with the server's public key and sends the result to server 40 (107). The client concurrently or subsequently retrieves its certificate (CERT-C) from storage (105) encrypts (106) the certificate with the secret session key and sends the result to server 40 (108). In the non-interactive embodiment, there is no signing by the server or even the generation and sending of a message by the server. The client's confidence in the server is assured by the use of the server's public key, since only the server can decrypt a message encrypted with its public key. The authenticity of the client is established to the satisfaction of the server by its receipt and verification of the time-varying value and the client's certificate by processing the received messages in accordance with the procedure shown in Figure 3B.

In the interactive embodiments of Figures 4A, 4B

and 4C, message 11 consists of a certificate (CERT-S), a time-varying value, or a combination of a certificate (CERT-S) and a time-varying value. These informational items are provided to a client so that the client may properly form authenticating message 12. Figure 5 shows an interactive embodiment where the server provides a signed message 11. Since Figure 5 is the most comprehensive, it will be described first, and the embodiments of Figures 4A, 4B and 4C described primarily with respect to differentiating features caused by the differences in the content of message 11.

In Figure 5, the parties to the electronic transaction are the client 20 and the server 40. Messages 11, 12 and 13 are generated and exchanged between the client 20 and the server 40 over a communications channel 15. Successful exchanges of the messages establish the trust of the client 20 in the server 40 and the authenticity of the client 20 to the server 40. Communications channel 15 may simply be electrical connections between a card reader and the terminal equipment at a server or may be in the form of a telephone or other communications link established between a client and a remote server, or other conventional communications medium.

Client 20 includes a certificate (CERT-C) 21 stored in EPROM 3, a key generator (KEY) 22, a facility for generating a time-varying value (TS) 23 which may include the clock 8, when used, and the public key (PUB_{TCA}) 24 of the trusted certification authority which may be stored in EPROM 3 or PROM 4. Certificate 21 comprises a message provided and signed by the trusted certification authority with its private key in the standard manner. The message in this instance need not be the client's public key because this key is not involved in the protocol. Any message is sufficient and may be certain well structured information about the client, e.g., account number and expiration date of the account. The message may also indicate the types of transactions for which the client 20 is authorized and the period of time during which the certificate may be considered valid. The key generator 22 is comprised of any conventional means of generating an encryption key. It may comprise a subroutine in the processor and use a number supplied by a number generator 7. The facility 23 may comprise conventional clock 8 that provides a current date and time or may be one that operates on a received timestamp or time-varying value. Key 24, the public key of the trusted certification authority, is used to verify a certificate sent by the server and signed by the trusted certification authority.

Key storage unit 25 represents an optional memory or memory section for storage of keys of one or more frequently used servers. These are the public keys of servers and are made available to clients by the servers. Storing the public key of server 40 and other selected servers at the client avoids the need to process the certificate from a server to recover the key, or provides a source for the key where the certificate does not contain the public key or an easily recoverable copy of the public key of the server. CRL storage unit 26, also an optional memory or memory section, stores a list of certificates that have been revoked.

Elements 30 through 35 illustrate the functional processes of the protocol performed by the client to establish trust in the server. Public key operations are conventional well known processes in the art. Recovering the public key of the server from the server's certificate for the key and storing it in a memory, as illustrated in block 30, is a certificate processing within the skill of art.

Functional element 32 represents a public key operation performed with the trusted certification authority's public key 24 on the certificate portion of the message 11 received from the server 40. Functional element 31 represents a public key operation performed on the timestamp or other time-varying value received from a server with the server's public key obtained from processing the certificate at read and store element 30 or from key storage unit 25. At functional block 33 a standard verification procedure, as those skilled in the art appreciate, is used to verify the certificate. A certificate revocation list supplied from memory 26 may optionally be used in verifying the certificate.

Functional element 34 represents a comparison and verification of the timestamp or time-varying value received from the server 40 to verify that it is proper. Where the smart card or client has a clock, a simple comparison (allowing for small time differences) of the time at clock 8 with the time of the received timestamp suffices to verify a received timestamp. Where the smart card does not include a clock, the stored time of a last received valid timestamp can be compared with the time of the currently received timestamp to verify that the currently received timestamp is later in time. Any time-varying value may be received and processed to verify that it is of recent origin or in a proper time sequence.

Failure to verify the server's certificate or time-varying value (illustrated by the NO outputs of elements 33 and 34) results in an error and termination of the transaction. Symbol 35 is a representation that permits further processing, i.e. the generation of the secret session key, when both the received certificate and time-varying have been verified (indicated by YES outputs of elements 33 and 34).

Elements 36, 37 and 38 illustrate the functional processes performed by the client 20 to generate messages 12 and 13. Message 12 is generated by concatenating the session key 22 and the time-varying value from facility 23 at element 36 and performing a public key encryption on the combination in public key operation 37 with the public key of server 40 retrieved from read and store element 30 or key storage unit 25. Message 13 is generated by performing an encryption at element 38 on the certificate 21 with the session key 22.

The functional elements and blocks of client 20 define operational steps performed by a processor, e.g., processor 2 of Figure 1. Similarly, the functional ele-

ments and blocks of server 40 illustrate operational steps performed by the server's processor 60.

Server 40 of Figure 5 includes a certificate (CERT-S) 41 provided by the trusted certification authority, a facility for generating time-varying values (TS) 42, the private key of the server ($PRIV_{SERV}$) 43 and the public key of the trusted certification authority (PUB_{TCA}) 44. Certificate 41 is a certificate for the server's 40 public key, and contains a message which includes the server's public key and that identifies the server as a valid and authorized holder of the public key. Facility 42 may be provided by a clock. The key 43 is the server's private key of the public key/private key pair used in standard public key cryptography. Key 44 is the public key of the trusted certification authority. CRL 45 is an optional element that stores certificate revocation lists for both server's and client's certificates. These lists are signed, dated messages received from the trusted certification authority. The server CRL is for forwarding to a client during the herein described protocol or ancillary to the protocol. The client CRL would serve, for example, as a list of revoked smart cards, i.e., cards that have been lost, stolen, destroyed or that have expired.

The server's certificate and private key, the public key of the certification authority and the CRL are stored in memories of the server. These memories are accessed by a processor of the server in accordance with an operating procedure for executing the authentication protocol.

Elements 17 and 18 illustrate the functional process for generating message 11. The time-varying value from facility 42 is signed with the private key 43 of the server 40 in private key operation 17. The signed time-varying value is then concatenated with the certificate 41 in the concatenate operation 18 to thereby form message 11.

Blocks and elements 51 through 56 represent functional processes of the protocol performed by the server 40. Functional element 51 performs a private key operation with the private key 43 on the received message 12. A comparison at 52 provides verification of the time-varying value received from the client 20. This may be done by comparing a timestamp received with the current timestamp of a clock from facility 42, or by storing a time-varying value sent to the client and comparing the stored time-varying value with the time-varying value returned by the client to see that they are in correspondence. Gate symbol 53 represents the permissive continuation of the processing upon the verification of the receipt of a proper time-varying value. Functional element 54 performs a decryption of the message 13 using a key 22 received from the client 20. Functional element 55 performs a public key operation on the certificate with the public key 44 of the trusted certification authority. Block 56 provides for the verification of the certificate with or without the CRL of clients in a manner well understood by those skilled in the art.

Initially, the client 20 may have to gain the trust of the server 40 before it will reveal its certificate 21. This protects against revealing the certificate to unauthorized third parties who could then use the certificate to impersonate client 20. Client 20 gains the trust of the server 40 through a public key protocol.

Considering the Figure 5 illustration, so that client 20 may gain its trust, upon a request for access the server 40 reveals its certificate 41 by combining the certificate 41 with the signed time-varying value from facility 42 to form message 11 CERT-S{TS}$PRIV_{SERV}$. Client 20 receives the message 11 sent over the communications channel 15, verifies the signature on the certificate with the trusted certification authority's public key 24 in public key operation 32 and verification process 33, and processes the certificate in operation 30 to read and store the public key of the server. Client 20 then uses the public key of the server in public key operation 31 to obtain the time-varying value. As indicated above, the public key of server 40 alternatively may be retrieved from public key storage unit 25 where used. Checking of the time-varying value to see that it is valid is done in comparison unit 34. A failure to verify the server's certificate or validate the received time-varying value terminates the transaction. Signature verification, particularly for RSA, is computationally inexpensive, so the computational burden on the client 20 is minimal. As an additional step in certificate verification, the client 20 may check the values of one or more fields of the certificate 41 to determine whether the server 40 is authorized for transactions with the client 20. It is presumed that the trusted certification authority of interest issues authorized certificates only to trusted servers, so the pair of signature verifications is sufficient for the client 20 to gain trust in the server 40.

Once client 20 verifies the time-varying value from 42 and the certificate 41 of server 40, trust of the server 40 is established. Thereafter, client 20 generates a random secret session key (KSS) at 22, combines this key with its time-varying value (TS) generated by a clock at 23, or where no clock is present replicates the time-varying value received from the server, to form a message and encrypts the message with the public key (PUB_{SERV}) of server 40 obtained from storage at element 30 or 25 to form the encrypted message 12. Again, for RSA, encrypting with the server's public key is computationally inexpensive so this is not a burden on the client.

The encrypted message 12, {KSSITS}PUB_{SERV}, is sent to the server 40 where it is received and processed for recovery of the secret session key KSS by decrypting the message 12 with private key 43 in private key operation 51. A checking of the time-varying value TS demonstrates to the server 40 that a client is active in the transaction, not an impersonator replaying a recorded message.

Client 20 then encrypts its certificate 21 using the secret session key to produce encrypted message 13, {CERT-C}KSS, and sends it to server 40. Messages 12 and 13 may be combined as one message {KSSITS} PUB_{SERV}{CERT-C} KSS. Server 40 receives the en-

crypted message 13 and decrypts it in decryption operation 54 to gain the client's 20 certificate 21. Certificate 21 is processed in public key operation 55 with the trusted certification authority's public key stored at 44. After verification at 56, with or without the optional CRL in unit 45, the authenticity of client 20 is accepted by server 40 and the transaction can be undertaken.

When clocks are used for both timestamp facilities, the client and the server need to account for variations in their clocks when checking that the timestamp received is current. One procedure is to determine the difference between the two clock timestamps, for example, the client determines the difference between the received timestamp and its own clock generated timestamp, and compares that difference to a pre-set reference value to see that it is less than the reference value. Other techniques known to those skilled in the art may be used to account for the clock variations. See, for example, Weiss, U.S. Patent 4,885,778, entitled "Method and Apparatus for Synchronizing Generation of Separate Free Running, Time Dependent Equipment," which describes a technique for synchronizing client and server clocks in an authorization protocol.

In place of a timestamp a challenge may be used. A challenge may comprise any-time varying message that can be processed and verified.

The client may also store a CRL of servers. Either as a part of the authentication protocol or subsequent thereto, the server and the client may exchange lists of revoked certificates.

In the embodiment illustrated in Figure 4A, message 11 consists of the public key certificate 41 of server 40. Here, client 20 does not have or need to have prior possession of the server's public key. Possession of the server's public key is acquired by the client receiving and reading the public key certificate 41. The signature on the certificate is verified with the Trusted Certification Authority's public key 24 and the certificate is verified by conventional verification procedures as discussed in the description of Figure 5. This public key of the server is then used in public key operation 37. The time-varying value is generated locally at facility 23. As seen from Figure 4A, client 20 comprises only the elements, e.g., 24, 32, 33 and 26 to verify the certificate and its signature and a functional element 30 to read the received certificate 41 and store the public key PUB_{SERV}. The server's processing to form message 11 involves only the sending of its certificate 41. The remainder of the components, functional elements and operations of figure 4A correspond with those in Figure 5.

In the embodiment of Figure 4B, the message 11 consists of certificate 41 and a time-varying value TS. The time-varying value TS is needed where a client 20 does not have a facility for generating its own time-varying value. Thus, as shown, server 40 forms message 11 by concatenating at element 18 the certificate 41 with the time-varying value from facility 42. In Figure 4B, client 20 verifies via 24, 32 and 33 the signature on the certificate, optionally via 26 the revocation status of the certificate and at functional element 39, reads and stores the server's public key and the time-varying value sent by the server. The time-varying value is processed and replicated or modified for use in forming message 12. This embodiment is advantageous since its implementation requires few structural components and computational operations. The client simply obtains the value TS and public key of the server needed for generating message 12 from the server. The server then processes the messages received as in the previously described embodiments. When a timestamp is not used by the server as the time-varying value, neither the server or the client needs a clock. Public key storage element 25 is optional.

In Figure 4C, message 11 consists of a time-varying value TS. As previously described, client 20 may have no clock or timestamp facility. It therefore has to receive a time-varying value at facility 23 or the like. Again, the received time-varying value may simply be replicated, or modified in a predetermined manner, and returned to server 40 in message 12. This assures the server that a current transaction is taking place. Again, neither party needs a clock. However, the client has to have a stored copy of the public key of server 40, i.e., an element 25 of memory 4 with a stored copy of the public keys of various servers with which it will interact. Server 40 only requires the message generating elements necessary to send a time-varying value. The remaining elements depicted in Figure 4C are like those in Figure 5 and operate in a similar manner.

The content of the messages generated and sent by a client to a server may be as shown in Figure 6. Here the time-varying value is concatenated with the certificate of the client instead of with the secret session key. As shown, client 20 in public key operation 37 encrypts the secret session key with the server's public key, the server's public key being produced as in any of the previously described embodiments, concatenates at 36 the time-varying value, obtained as in any of the previously described embodiments, with the client's certificate (CERT-C), and encrypts at 38 the result using the secret session key. The processing in the server is modified to accommodate the change in the messages 12 and 13, causing the time-varying value verification to be subsequent to the decrypting at 54. The server decrypts message 12 using its private key to recover the session key and decrypts the time-varying valuelcertificate with the secret session key. The certificate is subjected to a public key operation and verifying procedure as in elements such as 55 and 56 as shown in the Figure 5 embodiment. The variation shown in Figure 6 may be practiced with any of the embodiments hereinbefore described.

In some instances a session key in not used, as for example where the subsequent communications of the overall transaction session are not encrypted. The client's certificate is simply concatenated with a time-varying value and the result is encrypted with the server's

public key to form the message 12 which is sent directly to the server. Figure 7 shows, in part, a protocol that does not use a session key. The client 20 concatenates at 36 a time-varying value produced as in any of the previously described embodiments, and encrypts at 37 the result with the server's public key obtained as in any of the previously described embodiments. Server 40 decrypts the message at 51 with its private key, verifies at 52 the time-varying value, and processes the client's certificate as hereinbefore described to authenticate it. A smart card using this protocol may only comprise a processor, a memory storing the certificate for the card and the public key of servers and a facility for providing a time-varying value. The smart card may then engage in a non-interactive protocol with a server for the purpose of establishing its authenticity to a server. In an interactive protocol, the server in a communication to the client provides a time-varying value and its public key certificate as in Figure 4B, and the smart card processor processes the receipt of same to produce a time-varying value and the public key of the server. The other interactive embodiments of Figures 4A and 4C and Figure 5 may also be modified to have no session key.

It is also possible to modify the aforementioned embodiments to encrypt only part of the certificate, which may lead to greater efficiency in the protocol. For instance, the client can encrypt only the signature on the certificate, transmitting the rest of the certificate unencrypted. Since a certificate is not valid without a signature, an opponent who obtains only the non-signature part of the certificate will not be able to impersonate the client.

As a generalization, the client can encrypt any data essential to the verification of the certificate. The signature is one example; another example is a part of the signature, large enough so that the opponent cannot guess it. A third example is a secret certificate serial number assigned by the certification authority. In general, the most efficient approach, in terms of communication requirements, is to encrypt something that is already required by the server, rather than something new. Since the signature is already required, it is a natural choice, though other parts of the certificate may be appropriate as well.

In some cases, it may be more efficient in terms of communication bandwidth to encrypt more than just the data required to verify the certificate. For instance, if the encryption is performed with the public key of the server, then the client can encrypt as much additional data as can be encrypted with a single public-key encryption operation. The approach of encrypting the entire certificate is an extreme example. As another variation, it is possible to encrypt part of the certificate with a public-key encryption, and part with a secret-key encryption.

Figure 8 illustrates in part a variation of the embodiment of Figure 5 wherein only a portion of the certificate 21 is encrypted and transmitted to the server 40 with the remainder of the certificate (REST-C) being transmitted in unencrypted form. Thus, the certificate 21 can be split at 81 so that any data in the certificate which is essential to the verification of the certificate is split and subsequently encrypted by secret session key (KSS) at 38. The remainder of the certificate (REST-C) is transmitted unencrypted to the server 40.

Upon receipt of the transmitted encrypted and non-encrypted portions of the certificate the server 40 decrypts the former at 54 and joins the latter at element 82 so as to obtain the client's certificate 21. Thereafter as illustrated in Figure 5, the certificate is processed in public key operation 55 with subsequent verification at 56. As previously noted, the encrypted portion (X-C) of the client's certificate may be any portion which is sensitive or essential to the verification of the certificate such as the signature or a portion of the signature.

Figure 9 is an illustration of a variation of the embodiment of Figure 6 wherein only a portion (X-C) of the client's certificate 21 is encrypted with the remainder (REST-C) being transmitted in unencrypted form. In this regard the certificate 21 is again split at 81 to obtain an essential portion (X-C) of the certificate. Thereafter, as may be seen from Figures 9 and 6, the essential portion of the certificate is concatenated at 36, encrypted at 38 and transmitted to the server 40. Moreover, the unencrypted portion (REST-C) of the certificate 21 is transmitted to the server 40 for joining at 82 with the decrypted portion (X-C) for subsequent verification of the client's certificate 21.

Figure 10 illustrates a variation of Figure 7 wherein only an essential portion of the client's certificate 21 is encrypted with the remainder of the certificate being transmitted unencrypted. More specifically, the certificate 21 is split at 81 to form an essential portion (X-C) which is concatenated and encrypted at 36 and 37, respectively, for transmission to the server 40. Meanwhile, the rest of the certificate (REST-C) is transmitted to the server in unencrypted form for joining at 82 with the essential portion of the certificate as decrypted at 51 and 52 to thus provide the server with the client's certificate.

Another approach applies when the certificate contains a field that is computed as the one-way function, such as a cryptographic hash function, of a secret value. In this case, the secret value is encrypted and transmitted to the server, and the server computes and compares the one way function of the received secret value to the field in the certificate, after verifying the certificate. This has the advantage that the secret value can be concealed from the certification authority during the process of obtaining a certificate, so that the certification authority cannot later impersonate the client. The approach of encrypting a secret data value whose one-way function value is contained in the certificate has this property. A related approach is described in the Secure Electronic Transaction Specification (MasterCard and Visa, June 24, 1996). In SET, the name field in a certificate is formed as a one-way hash of the account number and other information, and during a purchase protocol, the

account number and the other information are encrypted and transmitted to a server, which compares their hash to the name field of the certificate. However, authentication in SET is also based on digital signatures, as in other conventional approaches. The account number itself is concealed for the protection of the account owner, not primarily for authentication, and it is not concealed from the certification authority.

Related to this, there could be a hash-tree of secret values whose root is included in the certificate, where a path through the tree is encrypted and transmitted to the server. The hash-tree variation provides greater protection against misuse by the server, since different paths could be associated with different servers. Here it is important to note that the path is encrypted. However, in a different approach based on a hash tree, the root is included in the certificate and a digital signature, which need not be encrypted, is formed with the tree. See, for example, Merkle, U.S. Patent 4,309,569, entitled "Method of Providing Digital Signatures." In this regard, the storage requirement for the latter approach is quite large and may be impractical in a smart card or similar processor.

Regarding hash trees, as may be seen in Figure 11, a hash tree consists of a root and one or more children, where if there is more than one child, each child must be a hash tree, and if there is only one child, the child is a leaf. A leaf has no children. A hash tree thus consists of many leaves, connected to the root through intermediate nodes. Each leaf has a predetermined value. The value of a hash tree is the hash of the values of its children and the value of a hash tree is thus computed recursively.

A path through a hash tree consists of a leaf and the values of the siblings of its successive parents. A path is verified by recalculating the value of the root based on the values in the path. This can be done recursively, since the value of each child of the root is either in the path, or can be recalculated from the rest of the path. As may be seen in Figure 11, the path from X_3: X_3, $h(X_4)$, $h(h(X_1), h(X_2))$ can be verified by recalculating the root given the values of siblings in the path.

Only one leaf is contained in a path, and provided that the hash function is one-way, the values of leaves not in a given path cannot be determined from the path. Thus, it is possible to reveal paths for each leaf in the tree such that a different path is used for each verifier, so as to prevent misuse. Only the root needs to be trusted initially by a verifier. It should be noted that the previously mentioned approach of storing the hash of a secret value in the certificate is really just a special case of a hash tree, where there is only one leaf.

In the above described protocols, the server 40 can easily recover the certificate sent by client 20 but no third party can because only client 20 and server 40 know the secret session key and/or only the server knows its private key. The server 40 is convinced that the client 20 is authentic and active in the transaction. Client 20 is assured that its certificate is seen only by server 40. While server 40 has enough information after a transaction to impersonate client 20, server 40 is of such integrity as to be trusted not to reveal the client's certificate to any third party or to impersonate client 20.

Trust of server 40 is a realistic consideration since servers are currently trusted to not reveal passwords or other data belonging to a client. In financial applications, the server (card reader) is trusted not to reveal account numbers or a personal identification number (PIN). Thus, it is reasonable to assume that the server or card reader will not reveal certificates.

In the case of RSA, the encryption and signature operations can follow the techniques described in PKCS #1: *RSA ENCRYPTION STANDARD* (RSA Laboratories, November 1993), in *International Standard 9796: Information Technology, Security Techniques: Digital Signature Scheme Giving Message Recovery (ISO/IEC, 1991)*, in *M. Bellare and P. Rogaway, "Optimal Asymmetric Encryption" in Advances in Cryptology - Eurocrypt* '94, *pp 92-111 (Springer-Verlag (New York* 1995)) or in similar standards, as are well known to those familiar with RSA.

The client and server certificates may be signed by the same trusted certification authority or different trusted certification authorities. The client and server, in either case, needs to have in its possession, the public key of the trusted certification authority that signed the received certificate in order to verify it.

In the above noted embodiments where the server's public key is provided to the client, the same server public key was used for encryption and verification. However, the public key of the server 40 for encryption may be different than the public key for verifying signatures. In Figure 5, for example, elements 31 and 37 could employ different public keys by storing two different public keys associated with the same server: one of which would be for verifying the server signatures at 31 and the other for encrypting data at 37 to be sent to the server. Alternatively, the certificate of the server could contain two separate keys along with identification as to their purposes. Moreover, in either alternative, element 43 of Figure 5, for example, would provide appropriately different private keys to elements 17 and 51.

As an additional modification to the disclosed exemplary embodiments, the client's certificate (CERT-C) may be generated once by the certification authority and stored in the client's memory 21 or it may be a certificate generated by a certification authority whenever the client is authenticated to the certification authority, e.g. as part of a daily log-in procedure. Moreover, the authentication operation could be carried out by techniques described herein or by other authentication techniques. The new certificate could also contain the time at which authentication occurred and could expire later at some set time. Thus, the exposure time of the certificate would be limited if it is obtained by an opponent. The new certificate could also specify the types of operations for

which the client is currently authenticated. Under such circumstances, the client would present the new certificate to the server to authenticate itself to the server, and the server would check that the certificate has not expired and that the client is authorized for a particular type of operation.

In financial applications, a certificate can be easily authenticated since it carries the digital signature of a certification authority. An account number cannot be easily authenticated because checking is done through accessing an on-line database. Therefore, in a financial application the certificate has clear benefits over an account number or an account number in combination with a PIN verification procedure.

In addition, if the account number contains check digits, they can usually be constructed by any third party with a public algorithm. Thus a third party can easily forge account numbers. For this reason, a database check is essential. Moreover, if the check digits are computed based on a secret key stored in the server, the same secret key must be stored in all servers. Therefore, an opponent who compromises one server can forge account numbers. This is another reason for the practice of having a central database perform the check. With certificates, the server stores only the trusted certification authority's public key, not the private key. Thus an opponent that compromises a server may obtain access to certificates known to that server, but does not gain the ability to form new ones.

As previously noted, the system as illustrated in Figure 12 is more fundamental and has a more general protocol whereby a user is enabled to confidentially deliver a credential authorizing the user to perform an operation. In order to reflect the more fundamental system and protocol the terms "user", "credential" and "verifier" are used rather than "client", "certificate" and "server", respectively, so as to indicate the more general nature of the Figure 12 exemplary embodiment. In Figure 12 the credential includes information essential to verify the credential which is transmitted to a verifier by way of an encrypted communications channel. In the illustrated system the user 60 may be an individual, a computer or some other entity. Moreover, the credential can be stored on a smart card or other device held by the user or may be held on the user's computer. Furthermore, the encrypted communications channel 65 can be between the user's smart card and the verifier or the user's computer and the verifier. Additionally, the verifier can be a client, a server or some other entity on a computer network having a secure channel connected to the user whereby at least data essential for verifying the user's credential is transmitted to the verifier.

Although the credential held by the user would include a digital signature by a credential issuing authority, it is only necessary for the system illustrated in Figure 12 to transmit some portion of the credential which would be necessary for verification of the credential to be transmitted to the verifier via the encrypted channel. That is to say, although the entire credential could be provided to the verifier via the encrypted channel, encryption could be limited to only portions essential for verification such as the digital signature on the credential, encryption of a secret value whose one way function value is stored in the credential or encryption of a path through a hash tree whose root is stored in the credential. Thus, element 62 would select all of the data of credential 61 or at least an essential portion thereof for transmission via the encrypted communication channel 66 for verification at 71 as illustrated in Figure 12. Other non-selected data would be transmitted through a non-encrypted channel and input to the verification step in a manner similar to that which is illustrated in Figures 8 through 10, for example.

Stated differently, with regard to the embodiment of Figure 12, although it is possible for all data of the credential to be transmitted through an encrypted channel, the primary focus of Figure 12 is that only data essential for verification need be transmitted through the encrypted channel. Additionally, it is important to note that the operation as illustrated in Figure 12 does not depend on operations with keys belonging to the user such as a digital signature by the user. Such keys, however, can be included in the credential, but verification operations do not depend thereon.

The credential can be verified by verifying the digital signature with the public key of the credential issuing authority and/or by performing other operations previously disclosed such as comparing the computed one way function of a transmitted secret value to the computed one way function of the secret value included in the credential or by checking the path through a hash tree.

With regard to the encrypted communications channel, the channel may comprise encryption with a secret key which is shared by both the user and the verifier, by the user's computer and the verifier or by encryption with the verifier's public key in a manner similar to that illustrated in the embodiment of Figure 7. Where a shared secret key is used, the secret key may be established by any of a number of techniques including the use of a third party key server, the user or the user's computer generating a random secret key and encrypting it with the verifier's public key and sending it to the verifier as in previously disclosed embodiments. Moreover, a time stamp or other non-repeating values may be included in the process of establishing the key as in previous embodiments or by encrypting the data necessary to verify the credential or both. Additionally, in the event that encryption on channel 66 uses the verifier's public key, as in previously disclosed embodiments, a certificate for the verifier's public key may be verified first by the user or its computer.

As in the previously disclosed embodiments, the verifier of Figure 12 is trusted not to reveal or misuse the user's credential. Moreover, since the data necessary to verify the credential is encrypted, the user is pro-

tected from opponents who cannot compromise the verifier's security. Moreover, since the credential includes a digital signature, the system is protected from opponents who can compromise the verifier's security since they can only reuse existing credentials and cannot generate new ones. In this regard, as noted with the previously disclosed embodiments, the user's credential can be obtained as a one-time value resulting from a successful log-in operation or can be obtained at some other interval. That is to say, the credential may authorize the user to perform certain operations and can also have further restrictions, such as limited time periods or limitations as to a list of authorized verifiers or servers.

In any event, the system as illustrated in Figure 12, for example, provides the fundamental features of allowing a user to confidentially deliver to a verifier information which is essential for verifying a credential assigned by a certification authority which authorizes the user to conduct some transaction wherein the credential may or may not involve the use of a one way function but always contains the digital signature of the credential issuer.

Moreover, although the system illustrated in Figure 12 merely illustrates the functional elements and blocks of a more fundamental system involving confidential delivery to a verifier of information essential for verifying whether a user is authorized to perform an operation, various features of the previously disclosed embodiments may also be included in the Figure 12 embodiment. For example, as previously noted, encryption on the encrypted communication channel 66 may be obtained with a shared secret key pre-installed with the user and verifier or established by encryption with the verifier's public key. Alternatively, other well known techniques for establishing a secret key by agreement can be used such as through the use of a Diffie-Hellman algorithm. Additionally, encryption as in the embodiments of Figures 4A through 7 may be obtained through the use of the verifier's public key or the use of a non-repeating value such as a time stamp. Moreover, as aforementioned, the entire credential may be encrypted or only essential data of the credential may be encrypted with the remainder of the credential being transmitted unencrypted in the manners illustrated in Figures 8 through 10, for example.

While the invention has been described in connection with what is presently considered to be the most practical and preferred embodiment, it is to be understood that the invention is not to be limited to the disclosed embodiment, but on the contrary, is intended to cover various modifications and equivalent arrangements included within the spirit and scope of the appended claims.

Claims

1. A method for establishing the authenticity of a client in a client-server electronic transaction where a server having a public key/private key pair and a certification authority's public key and a client having a certificate signed by the certification authority are coupled by a communications channel comprising,

   the client,

   a) generating a secret session key,
   b) producing a time-varying value,
   c) concatenating one of the secret session key or the certificate with the time-varying value,
   d) encrypting the secret session key or the secret session key concatenated with said time-varying value with the server's public key to produce a first message,
   e) encrypting at least a part of the certificate or the certificate concatenated with the time-varying value with said secret session key to produce a second message, and
   f) sending the first and second messages to the server, where a decrypting operation by the server on the first message with the private key of the public key/private key pair provides the server with the secret session key, a decrypting operation on the second message with the secret session key provides the server with at least a part of the client's certificate, the decrypting operation with one of the keys provides the time-varying value, and a verifying operation on the time-varying value and a public key operation with the certification authority's public key and verifying operation on the client's certificate establish the authenticity of the client.

2. A method as in claim 1 wherein the client's certificate comprises structural information about the client but no public key.

3. A method as in claim 2 further including said server sending a time-varying value to the client, said client using the received time-varying value for the time varying-value that is concatenated with the secret session key or the certificate.

4. A method as in claim 1 further including the server sending a time-varying value to the client, said client using the received time-varying value for the time-varying value that is concatenated with the secret session key or the certificate.

5. A method as in claim 1 wherein establishing the authenticity of the client is non-interactive.

6. A method as in claim 2 wherein establishing the authenticity of the client is non-interactive.

7. A method as in claim 1 wherein the certificate in-

cludes a first data portion which is essential for verification of the certificate and a second data portion, said method prior to executing step e) splitting said first data portion from said second data portion, sending said second data portion to the server without encryption, encrypting and decrypting the second message in steps e) and f), respectively, only said first data portion, of the certificate, joining said first and second data portions at the server and thereafter performing the verifying operation of step f).

8. A method as in claim 1, wherein the certificate includes data essential for verification of the certificate as well as non-essential data and only the essential data is encrypted and decrypted respectively in steps e) and f).

9. A method as in claim 4, wherein the certificate includes data essential for verification of the certificate as well as non-essential data and only the essential data is encrypted and decrypted respectively in steps e) and f).

10. A method for establishing the authenticity of a client in a client-server electronic transaction where a server and a client are coupled by a communications channel, comprising,

establishing a client's trust in the server over the communications channel,
the client having stored in a memory a certificate and the server's public key, and

(a) generating in a processor, upon having established the trust in the server, a secret session key, encrypting the secret session key with the server's public key and sending the encrypted secret session key as a message to the server over the communications channel, and
(b) encrypting at least a part of said certificate with said secret session key and sending the results of the encryption to the server over the communications channel,

whereby decryption with the server's private key associated with the server's public key by the server yields the secret session key and decryption of the results by the server with the secret session key produces at least a part of the client's certificate which is proof of the client's authenticity.

11. A method as in claim 10 where said certificate for the client includes structured information about the client but no public key.

12. A method as in claim 11 wherein said server has a public key certificate for its public key and steps in the method include sending said public key certificate to the client, said client processing the public key certificate to verify it and to recover and store the server's public key and using the recovered public key or a different public key of the server in the step of encrypting the secret session key or the secret session key concatenated with a time-varying value.

13. A method as in claim 12 further including said server sending a time-varying value to the client, said client using the received time-varying value for the time-varying value that is concatenated with the secret session key.

14. A method as in claim 10 wherein said server has a public key certificate for its public key and steps in the method include sending the public key certificate to the client, said client processing the public key certificate to verify it and to recover the server's public key and using the recovered public key or a different public key of the server in encrypting the secret session key or the secret session key concatenated with a time-varying value.

15. A method as in claim 14 further including the server sending a time-varying value to the client, said client using the received time-varying value for the time varying value that is concatenated with the secret session key.

16. A method as in claim 14, wherein the client's certificate includes data essential for verification of the client's certificate as well as non-essential data and only the essential data is encrypted and decrypted.

17. A method as in claim 10 wherein the step of establishing a client's trust in the server includes the client performing a public key operation with a stored certification authority's public key for the verifying of a certificate received from the server, processing the certificate received from the server to recover the public key of the server, storing the public key of the server in said memory and performing a public key operation with the server's public key for recovering an encrypted time-varying value received from the server.

18. A method as in claim 17 including generating a time-varying value and concatenating that time-varying value with the secret session key prior to the step of encrypting with the server's public key or with the certificate prior to the step of encrypting with the secret session key.

19. A method as in claim 18 wherein said server has

stored in memory its private key corresponding to said server's public key and the trusted certification authority's public key, and has a facility for generating a time-varying value,

said server receiving said message and in a processor, decrypting said message with said private key to recover said secret session key, using said secret session key in a decrypting operation to recover the at least a part of the client's certificate sent by the client, one of the decrypting operations providing the client's time-varying value, checking the client's time-varying value by comparing it with a time-varying value from the facility and verifying the client's certificate in a public key operation using the trusted certification authority's public key.

20. A method as in claim 19 wherein said server further includes stored in memory a certificate revocation list and the step of verifying the client's certificate includes checking the certificate revocation list.

21. A method as in claim 20 wherein the client has stored in memory a certificate revocation list and includes exchanging certificate revocation lists between the server and the client.

22. A method as in claim 18 including combining steps (a) and (b) to provide a message, and sending the message over the communications channel in one sending operation.

23. A method as in claim 18 including using a clock for generating the time-varying value in the form of a timestamp.

24. A method as in claim 18 including generating the time-varying value by using the time-varying value received from the server.

25. A method as in claim 10 wherein the generating of a secret session key includes the step of using a random number generated from a random number generator.

26. A method as in claim 10 wherein the certificate includes a first data portion which is essential for verification of the certificate and a second data portion, said method prior to executing step a) splitting said first data portion from said second data portion, sending said second data portion to the server without encryption, encrypting in step a) and decrypting at the server only said first data portion, and joining said first and second data portions at the server after decrypting said results.

27. A method as in claim 10 wherein the certificate includes data essential for verification of the certificate as well as non-essential data and only the essential data is encrypted and decrypted respectively by the client and server.

28. A smart card comprising a processor, a read only memory and an input/output port,

said processor including

means for producing a trusted server's public key, and
means for executing a protocol stored in said memory for establishing the authenticity of the smart card to a trusted server and for generating a secret session key,

said read only memory having stored therein a certificate for the smart card,
said protocol including encrypting the secret session key with the trusted server's public key and sending the encrypted secret session key to the trusted server over the input/output port, said protocol further including encrypting at least a part of said certificate for the smart card with said secret session key and sending the encrypted certificate to the trusted server over the input/output port.

29. A smart card as in claim 28 wherein said read only memory has stored therein a plurality of public keys belonging to respectively different servers which may be used as a source from which the trusted sewers' public key is produced.

30. A smart card as in claim 28 further comprising a facility for providing a time-varying value and means for concatenating the time-varying value with the secret session key or the certificate.

31. A smart card as in claim 30 wherein said facility for providing a time-varying value comprises a clock.

32. A smart card as in claim 30 wherein said facility for providing a time-varying value comprises means for storing a received time-varying value from a server and for supplying it or a modification thereof as the time-varying value of the smart card.

33. A smart card as in claim 30 wherein said processor further comprises means for establishing trust in a server, said means including using a public key operation with a certification authority's public key for establishing the identity of a server and a timestamp of the facility for providing a time-varying value for establishing that a message received from a server comprising a timestamp is current.

34. A smart card as in claim 28 wherein said certificate for the smart card includes structured information

about the smart card but no public key.

35. A smart card as in claim 28 wherein said means for producing a trusted server's public key includes processing a public key certificate received from a server.

36. A smart card as in claim 34 further comprising a timestamp facility providing timestamps for verifying received timestamps and supplying a timestamp to messages generated by the smart card.

37. A smart card as in claim 28 further comprising

a timestamp facility,
a number generator,
said protocol including,
establishing a server as a trusted server by a public key operation using the public key of the server to verify any message received from a server over the input/output port, using the timestamp to verify a timestamp received from the server and the public key of the trusted certification authority to verify a certificate provided by the server, and after the verifications,
generating the secret session key using a number supplied by the number generator,
concatenating a timestamp provided by said timestamp facility with the secret session key and encrypting with the public key used for verification or with a different public key of said trusted server the concatenated timestamp and secret session key, and
sending the encrypted result to the trusted server over the input/output port.

38. A smart card as in claim 28 wherein the certificate includes a first data portion which is essential for verification of the certificate and a second data portion and said protocol includes splitting said first and second data portions, encrypting only said first data portion, and sending the encrypted first data portion and an unencrypted second data portion to the server.

39. A server having a protocol for interactively engaging with and verifying the authenticity of a client of limited computational capacity comprising,

a memory storing a private key of the private key/public key pair of the server and a trusted certification authority's public key,
a facility for generating time-varying values,
a processor for performing the protocol,
said protocol including,

receiving and processing from said client a message including a session key encrypted with the server's public key and at least a part of the client's certificate encrypted with the session key, one of said session key and said at least a part of the client's certificate being concatenated with a time-varying value, said processing including
performing a private key operation on the message with the server's private key to recover the session key, decrypting the message with the session key to recover at least part of the client's certificate, receiving the time-varying value from the message and checking it with the current time-varying value of the facility to see that the client's time-varying value is proper, performing a public key operation on the at least part of the client's certificate with the trusted certification authority's public key and verifying the client's certificate.

40. A server as in claim 39 further including in a CRL memory a certificate revocation list and wherein the step of verifying the client's certificate includes checking the certificate revocation list for the presence of the client's certificate.

41. A server as in claim 40 wherein the protocol further includes a step of exchanging certificate revocation lists with the client.

42. A server as in claim 39 wherein said memory stores a certificate for the server's public key, and said server providing to a client, a time-varying value, the server's public key certificate or both.

43. A server as in claim 39 wherein the message from the client includes a first data portion of the client's certificate encrypted with the session key and a second data portion of the client's certificate which is not encrypted, said protocol including decrypting the first data portion of the client's certificate and joining the decrypted first data portion with the second data portion.

44. A smart card comprising a processor, a read only memory, an input/output port, and a facility for producing a time-varying value,

said processor including means for producing a server's public key and means for executing a protocol stored in said memory for establishing the authenticity of the smart card to a trusted server,
said memory having stored therein a certificate for the smart card,
said protocol including concatenating at least a part of the certificate with a time-varying value provided by said facility, encrypting the result of

the concatenating with the server's public key to form a message and sending the message via the input/output port.

45. A smart card as in claim 44 wherein said facility for providing a time-varying value comprises a clock.

46. A smart card as in claim 44 wherein the means for producing a server's public key includes receiving, processing and verifying a public key certificate of the server provided at the input/output port during a transaction.

47. A smart card as in claim 46 wherein the server's public key used for verifying and encrypting are different public keys of the server.

48. A smart card as in claim 44 wherein said facility for providing a time-varying value comprises means for receiving a time-varying value via the input/output port and for supplying it or a modification thereof as the time varying value of the smart card.

49. A smart card as in claim 48 wherein the means for producing a server's public key includes receiving and processing and verifying a public key certificate received from a server at the input/output port.

50. A smart card as in claim 44 wherein said certificate for the smart card includes structured information about the smart card but no public key.

51. A smart card as in claim 44 wherein the certificate includes a first data portion and a second data portion and said protocol concatenates and encrypts only the first data portion and the message sent via the input/output port includes an encrypted first data portion and an unencrypted second portion.

52. A method for establishing the authenticity of a client in a client-server electronic transaction where a server having public key/private key pairs and a certification authority's public key and a client having a certificate signed by the certification authority are coupled by a communications channel comprising

the client,
producing a time-varying value, concatenating the time-varying value with at least part of said certificate, encrypting the concatenated result with the server's public key to produce a message, and sending the message to the server,
the server,
decrypting the message using the private key of the public key/private key pair recovers the time-varying value and at least part of the client's certificate, verifies the time-varying value and processes at least part of the certificate using the certification authority's public key and verifies it, establishing the authenticity of the client.

53. A method as in claim 52 wherein the certificate includes a first data portion and a second data portion and only the first data portion is concatenated and encrypted and the message sent to the server includes an encrypted first data portion and an unencrypted second data portion, said server decrypting the first data portion and joining the decrypted first data portion and the second data portion.

54. A method as in claim 53 wherein the first data portion of the certificate comprises at least a portion of a digital signature on the certificate.

55. A method as in claim 52 wherein the client's certificate comprises structural information about the client but no public key.

56. A method as in claim 55 wherein said server has a public key certificate for its public key and steps in the method include sending said public key certificate to the client, said client processing the public key certificate to verify it and to recover the server's public key and using the public key in the step of encrypting the concatenated result.

57. A method as in claim 56 further including said server sending a time-varying value to the client, said client using the received time-varying value for the time-varying value that is concatenated with at least part of the certificate.

58. A method as in claim 55 further including said server sending a time-varying value to the client, said client using the received time-varying value for the time-varying value that is concatenated with at least part of the certificate.

59. A method as in claim 52 wherein said server has a public key certificate for its public key and steps in the method include sending the public key certificate to the client, said client processing the public key certificate to verify it and to recover the server's public key and using the recovered public key in encrypting at least part of the certificate concatenated with a time-varying value.

60. A method as in claim 59 further including the server sending a time-varying value to the client, said client using the received time-varying value in the step of producing a time-varying value.

61. A method as in claim 52 further including the server sending a time-varying value to the client, said client using the received time-varying value for the time-

varying value that is concatenated with at least part of the certificate.

62. A method as in claim 52 wherein establishing the authenticity of the client is non-interactive.

63. A method as in claim 55 wherein establishing the authenticity of the client is non-interactive.

64. A method as in claim 52 wherein said server has a public key certificate for its public key and steps of the method include sending said public key certificate to the client, said client processing the public key certificate to verify it and wherein the client and server use a second public key/private key pair to encrypt/decrypt, respectively, the message.

65. A method for determining at a verifier whether a user is authorized to perform an operation, said method comprising the step of obtaining from said user a credential authorizing said user to perform said operation, wherein

said credential includes a digital signature by a credential issuing authority;
at least data essential to verify said credential is transmitted from said user to said verifier through an encrypted communications channel; and
wherein the determination of authorization does not depend on an operation with a public key belonging to said user.

66. A method as in claim 65, wherein the credential includes data essential for verification of the credential as well as non-essential data and only the essential data is encrypted and the non-essential data is sent to the verifier unencrypted.

67. A method as in claim 66 wherein the credential includes a field computed as a one-way function of a secret value, the secret value is encrypted and sent to the verifier and the verifier computes and compares the one way function of the secret value to the field.

68. A method as in claim 66 wherein the credential includes a root of a hash tree and a path through the hash tree is encrypted and sent to the verifier.

69. A method as in claim 65 wherein the communication channel is encrypted with a secret key shared by the user and the verifier.

70. A method as in claim 65 wherein the communication channel is encrypted with a key established by using a key agreement technique.

71. A method as in claim 65 wherein the communication channel is encrypted with a key established by encryption with the verifier's public key.

72. A method as in claim 71 wherein the verifier's certificate is provided to the user and the user verifies the certificate.

73. A method as in claim 71 wherein the key is established by encryption with the verifier's public key and a non-repeating value is included with the data essential for verification.

74. A method as in claim 65 wherein the communication channel is encrypted with the verifier's public key and a non-repeating value is included with the data essential for verification.

75. A method as in claim 65 wherein the verifier's certificate is provided to the user and the user verifies the certificate.

76. A method as in claim 65 wherein the entire credential is transmitted to the verifier through the encrypted communications channel.

77. A method as in claim 65 wherein the data essential to verify the credential includes at least the digital signature.

78. A method as in claim 65 wherein the data essential to verify the credential includes at least a secret value whose one-way function value is contained in the credential.

79. A method as in claim 65 wherein the data essential to verify the credential includes at least a path through a hash tree whose root is contained in the credential.

80. A method as in claim 77 wherein the verifier checks the digital signature using the credential issuing authority's public key.

81. A method as in claim 78 wherein the verifier computes and compares the one-way function of the secret value with the one-way function value of the credential.

82. A method as in claim 79 wherein the verifier checks the path through the hash tree using the root contained in the credential.

83. A method as in claim 66 wherein the verifier checks the credential using the credential issuing authority's public key.

84. A method as in claim 65 wherein the credential is

issued as a result of successful authentication to the credential issuing authority.

85. A method as in claim 65 wherein the credential issuing authority is the verifier.

86. A method as in claim 84 wherein the credential issued includes a field computed as a one-way function of a secret value, the secret value is not revealed to the credential issuing authority and the secret value is transmitted as essential data.

87. A method as in claim 84 wherein the credential issued includes a root of a hash tree and a path through the hash tree is transmitted as essential data through the encrypted communication channel and wherein one or more leaves of the hash tree are not revealed to the credential issuing authority.

88. A method as in claim 84 wherein the determination of authorization includes a determination that the credential is not included in a credential revocation list.

89. A method as in claim 65 wherein the credential includes data specifying the types of operations for which the user is authorized; or the time at which the credential expires or a list of authorized verifiers.

90. A method as in claim 65 wherein the credential includes the user's public key but the user's public key is not used in the determination of authorization.

91. A system for determining whether a user is authorized to perform an operation with a verifier, said system comprising:

a user element for providing all or at least a part of the data included in a credential, said user element also providing data essential to verify the credential, said credential including at least a digital signature by a credential issuing authority;
said user element having a protocol for engaging with the verifier and including a device which selects data for transmission to the verifier, said data selected by the device including at least data essential to verify the credential;
an encrypted communication channel responsive to the device for transmitting data between the user element and the verifier, and
the verifier including a protocol for determining whether the user is authorized to perform an operation wherein the determination does not depend on the transmission of a user's public key from the user element.

92. A system as in claim 91 wherein the encrypted communication channel is encrypted with a secret key shared with the verifier or with the verifier's public key and a non-repeating value.

93. A system as in claim 91 further including a non-encrypted channel for transmitting between the user element and the verifier data which is non-essential data for verifying the credential.

94. A system as in claim 93 wherein the credential includes a field computed as a one-way function of a secret value and the secret value is selected, encrypted and sent to the verifier as essential data and the protocol of the verifier causes the verifier to compute and compare the one way function of the secret value to the field.

95. A system as in claim 93 wherein the credential includes a root of a hash tree and a path through the hash tree is selected as essential data and transmitted to the verifier.

96. A system as in claim 93 wherein the data essential to verify the credential is the entire credential or the digital signature on the credential or a secret value whose one way function is included in the certificate or a path through a hash tree whose root is included in the credential.

97. A system as in claim 93 wherein the credential includes data specifying the types of operations for which the user is authorized, or the time at which the credential was issued or the time at which the credential expires.

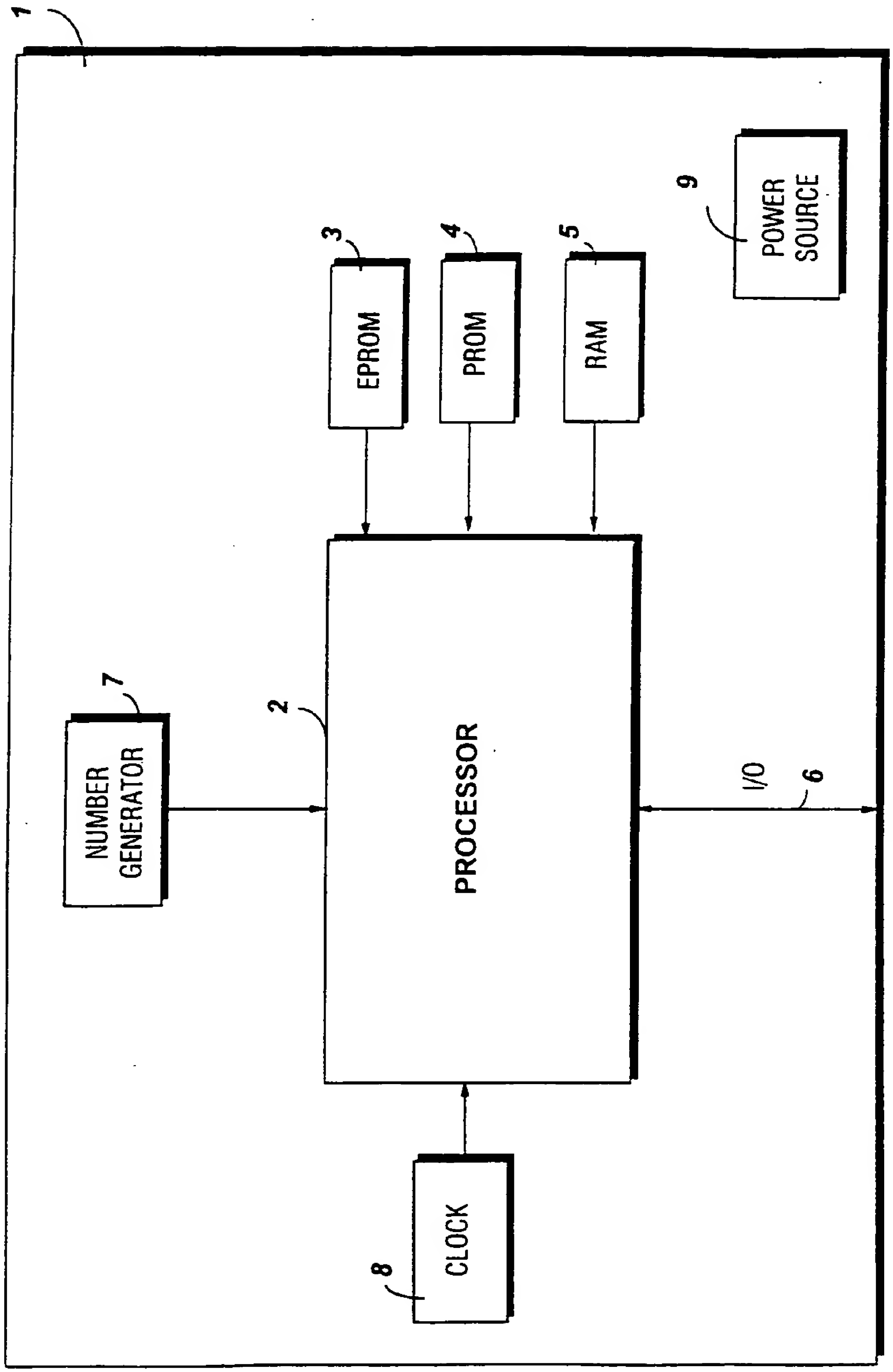

1
NUMBER GENERATOR
7
2
PROCESSOR
EPROM
3
PROM
4
RAM
5
POWER SOURCE
9
I/O
6
CLOCK
8

Fig. 1

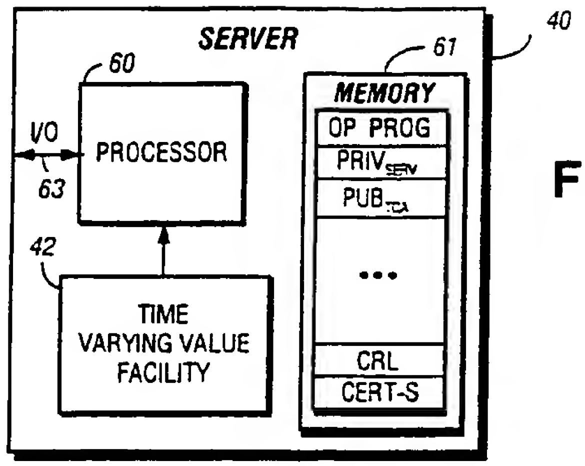

40
SERVER
60
61
MEMORY
I/O
63
PROCESSOR
OP PROG
PRIV
PUB
42
TIME VARYING VALUE FACILITY
CRL
CERT-S

Fig.2

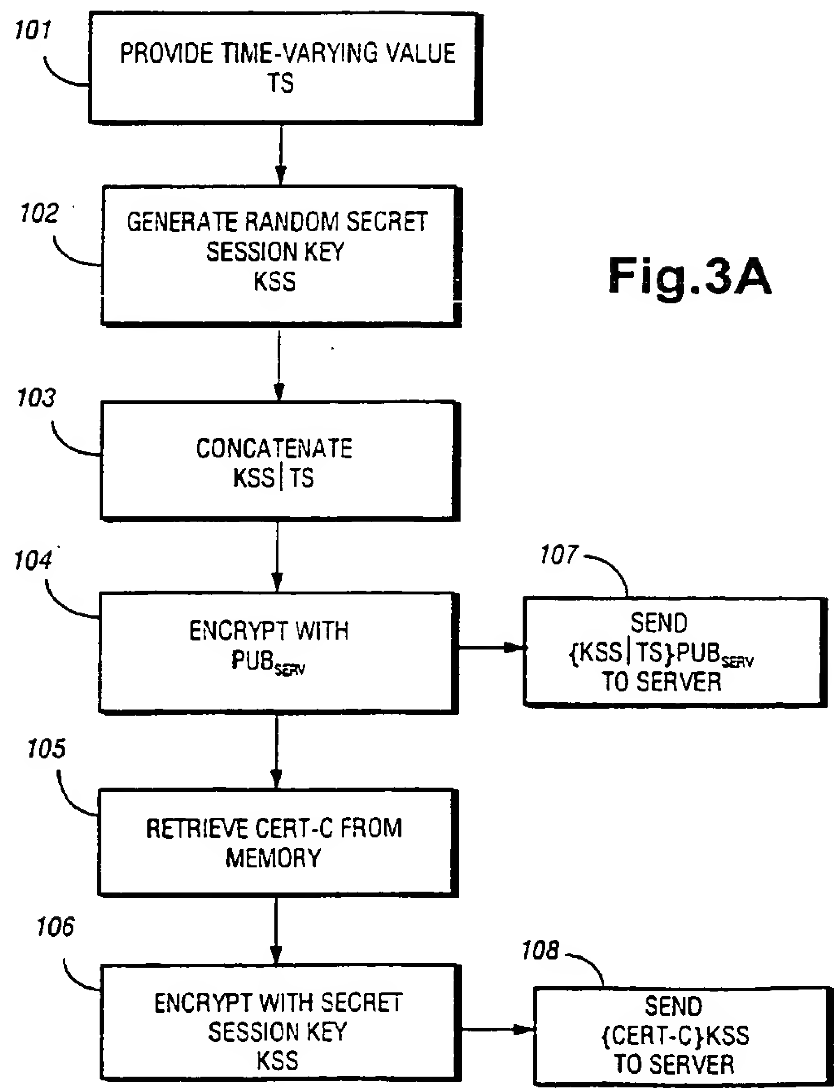
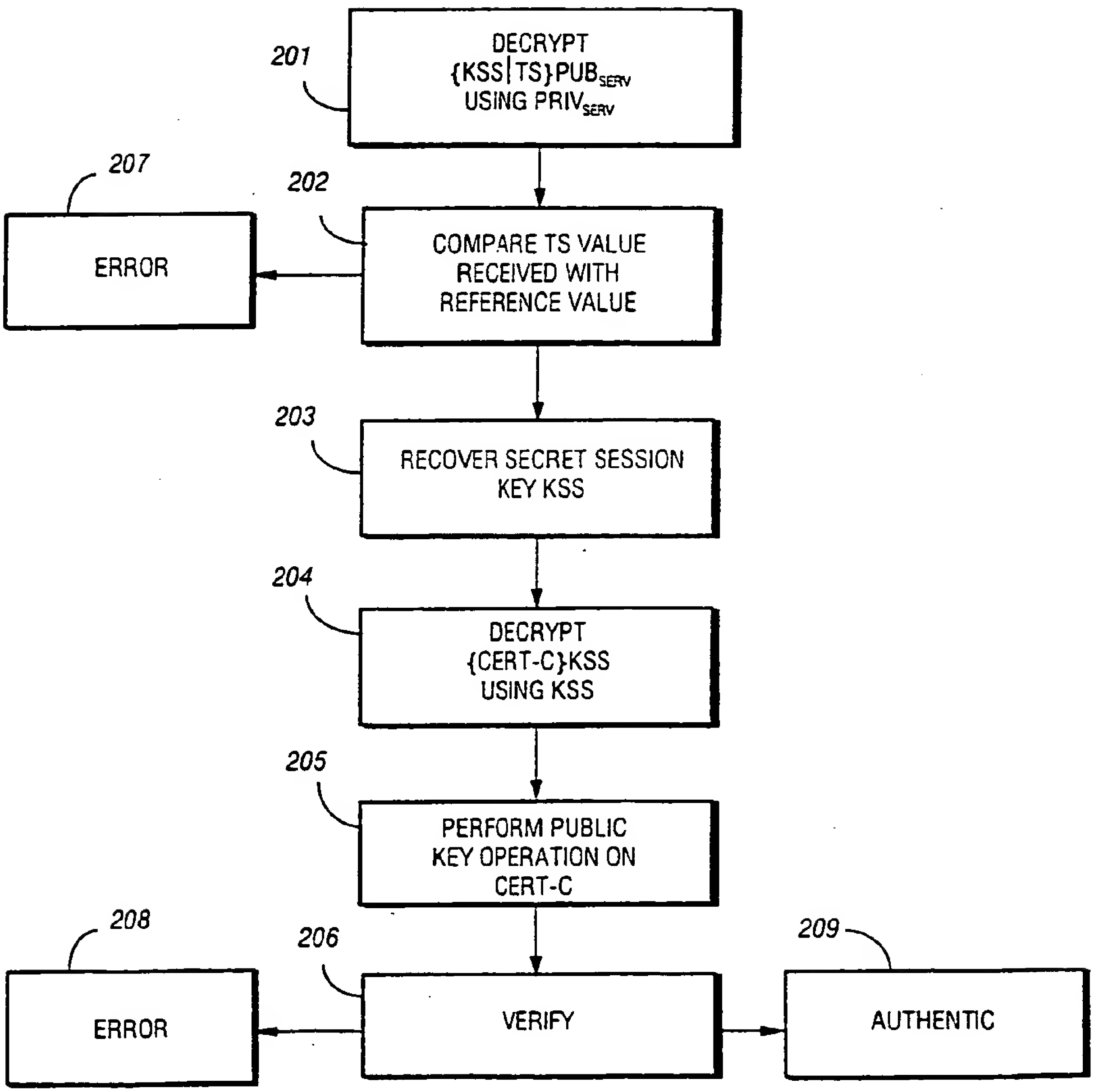

101
PROVIDE TIME-VARYING VALUE TS
102
GENERATE RANDOM SECRET SESSION KEY KSS
103
CONCATENATE KSS|TS
104
ENCRYPT WITH PUB
107
SEND {KSS|TS}PUB TO SERVER
105
RETRIEVE CERT-C FROM MEMORY
106
ENCRYPT WITH SECRET SESSION KEY KSS
108
SEND {CERT-C}KSS TO SERVER

Fig.3A

Fig.3B


201
DECRYPT
{KSS|TS}PUB$_{SERV}$
USING PRIV$_{SERV}$
207
202
ERROR
COMPARE TS VALUE
RECEIVED WITH
REFERENCE VALUE
203
RECOVER SECRET SESSION
KEY KSS
204
DECRYPT
{CERT-C}KSS
USING KSS
205
PERFORM PUBLIC
KEY OPERATION ON
CERT-C
208
206
209
ERROR
VERIFY
AUTHENTIC

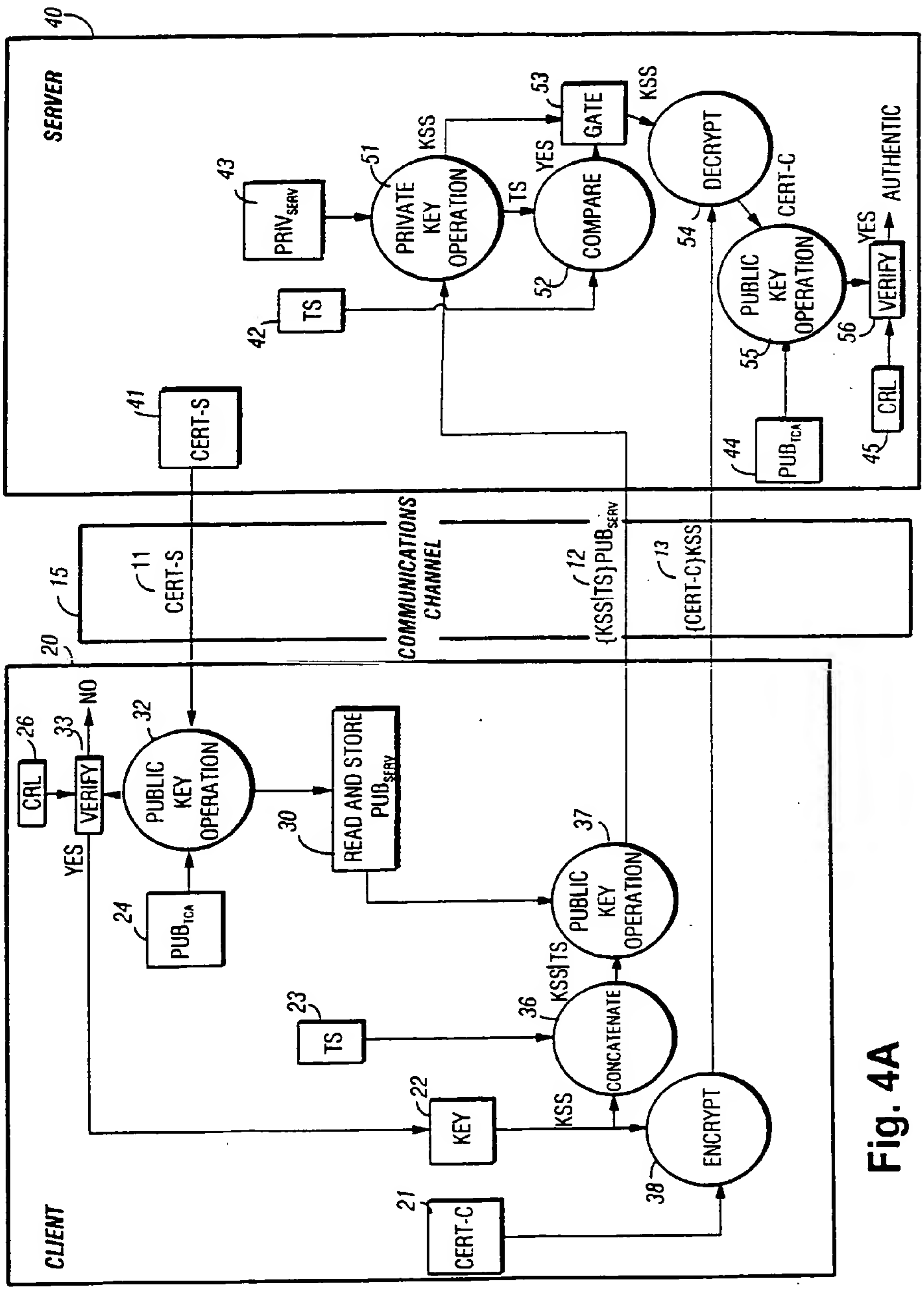

SERVER
40
41
CERT-S
43
PRIV$_{SERV}$
42
TS
51
PRIVATE KEY OPERATION
KSS
TS
52
COMPARE
YES
53
GATE
KSS
54
DECRYPT
CERT-C
55
PUBLIC KEY OPERATION
56
VERIFY
YES
AUTHENTIC
44
PUB$_{TCA}$
45
CRL
15
COMMUNICATIONS CHANNEL
11
CERT-S
12
{KSS|TS}PUB$_{SERV}$
13
{CERT-C}KSS
20
CLIENT
26
CRL
33
VERIFY
NO
YES
32
PUBLIC KEY OPERATION
24
PUB$_{TCA}$
30
READ AND STORE PUB$_{SERV}$
37
PUBLIC KEY OPERATION
23
TS
36
CONCATENATE
KSS|TS
22
KEY
KSS
38
ENCRYPT
21
CERT-C

Fig. 4A

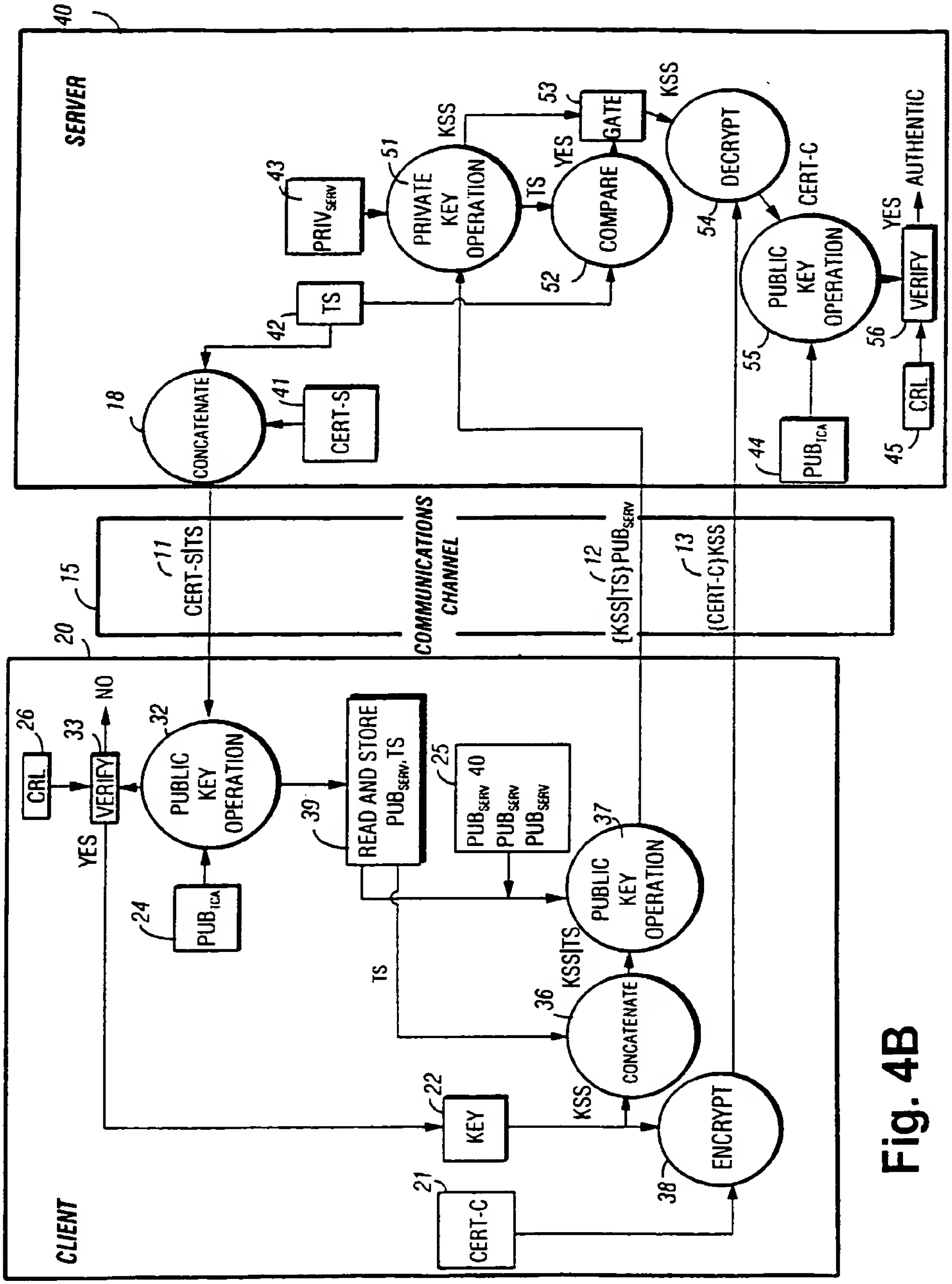
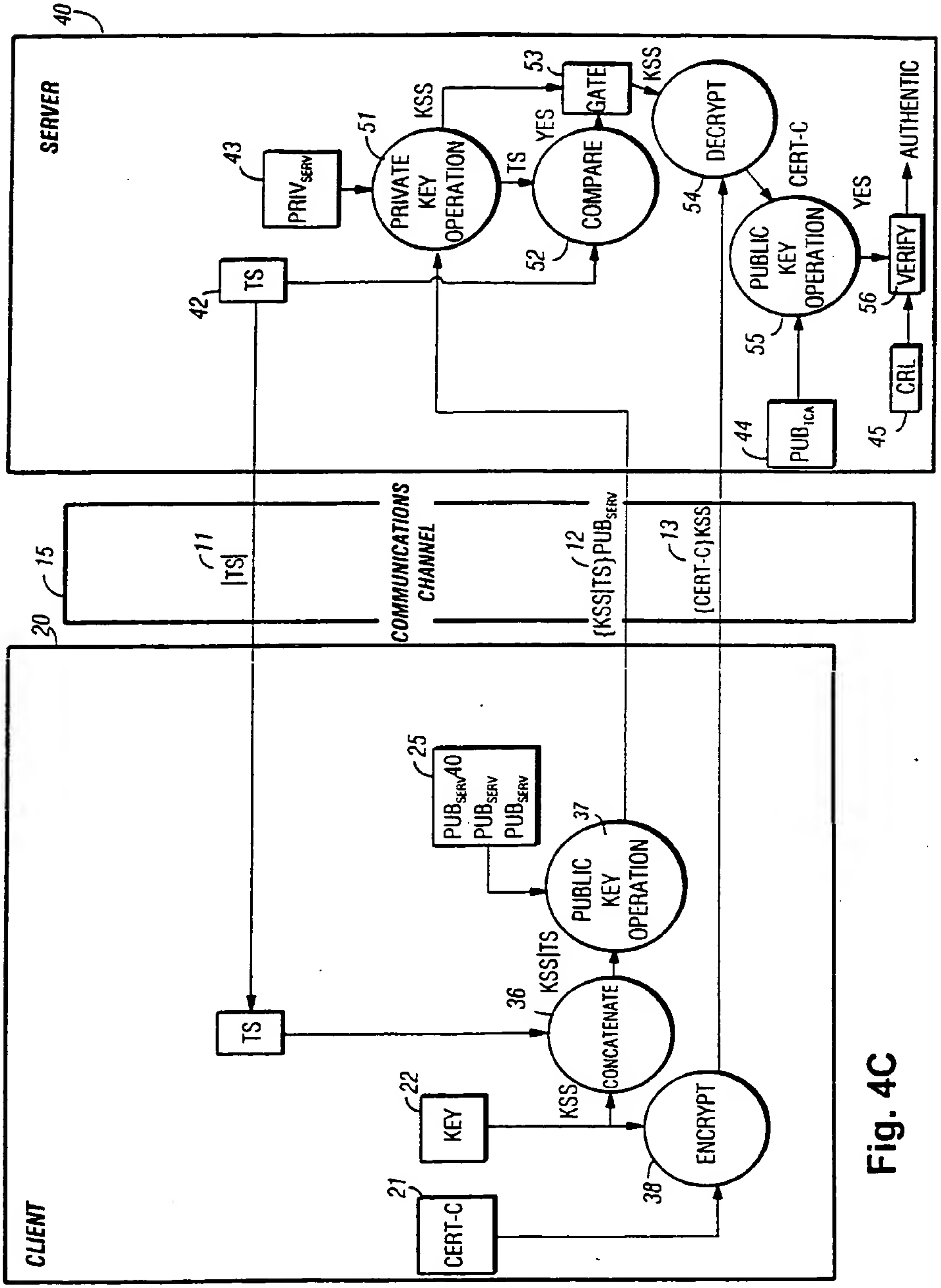

SERVER
40
CONCATENATE
18
CERT-S
41
TS
42
PRIV$_{SERV}$
43
PRIVATE KEY OPERATION
51
KSS
TS
COMPARE
52
YES
GATE
53
KSS
DECRYPT
54
CERT-C
PUBLIC KEY OPERATION
55
YES
AUTHENTIC
VERIFY
56
CRL
45
PUB$_{TCA}$
44
COMMUNICATIONS CHANNEL
15
CERT-S|TS
11
{KSS|TS}PUB$_{SERV}$
12
{CERT-C}KSS
13
CLIENT
20
CRL
26
VERIFY
33
NO
YES
PUBLIC KEY OPERATION
32
PUB$_{TCA}$
24
READ AND STORE PUB$_{SERV}$, TS
39
PUB$_{SERV}$ 40
PUB$_{SERV}$
PUB$_{SERV}$
25
PUBLIC KEY OPERATION
37
TS
KSS|TS
CONCATENATE
36
KEY
22
KSS
ENCRYPT
38
CERT-C
21

Fig. 4B



SERVER
40
TS
42
PRIV$_{SERV}$
43
PRIVATE KEY OPERATION
51
KSS
GATE
53
TS
YES
COMPARE
52
KSS
DECRYPT
54
CERT-C
PUBLIC KEY OPERATION
55
YES
VERIFY
56
AUTHENTIC
PUB$_{ICA}$
44
CRL
45
COMMUNICATIONS CHANNEL
15
|TS|
11
{KSS|TS}PUB$_{SERV}$
12
{CERT-C}KSS
13
CLIENT
20
PUB$_{SERV}$40
PUB$_{SERV}$
PUB$_{SERV}$
25
PUBLIC KEY OPERATION
37
TS
KSS|TS
CONCATENATE
36
KEY
22
KSS
ENCRYPT
38
CERT-C
21

Fig. 4C

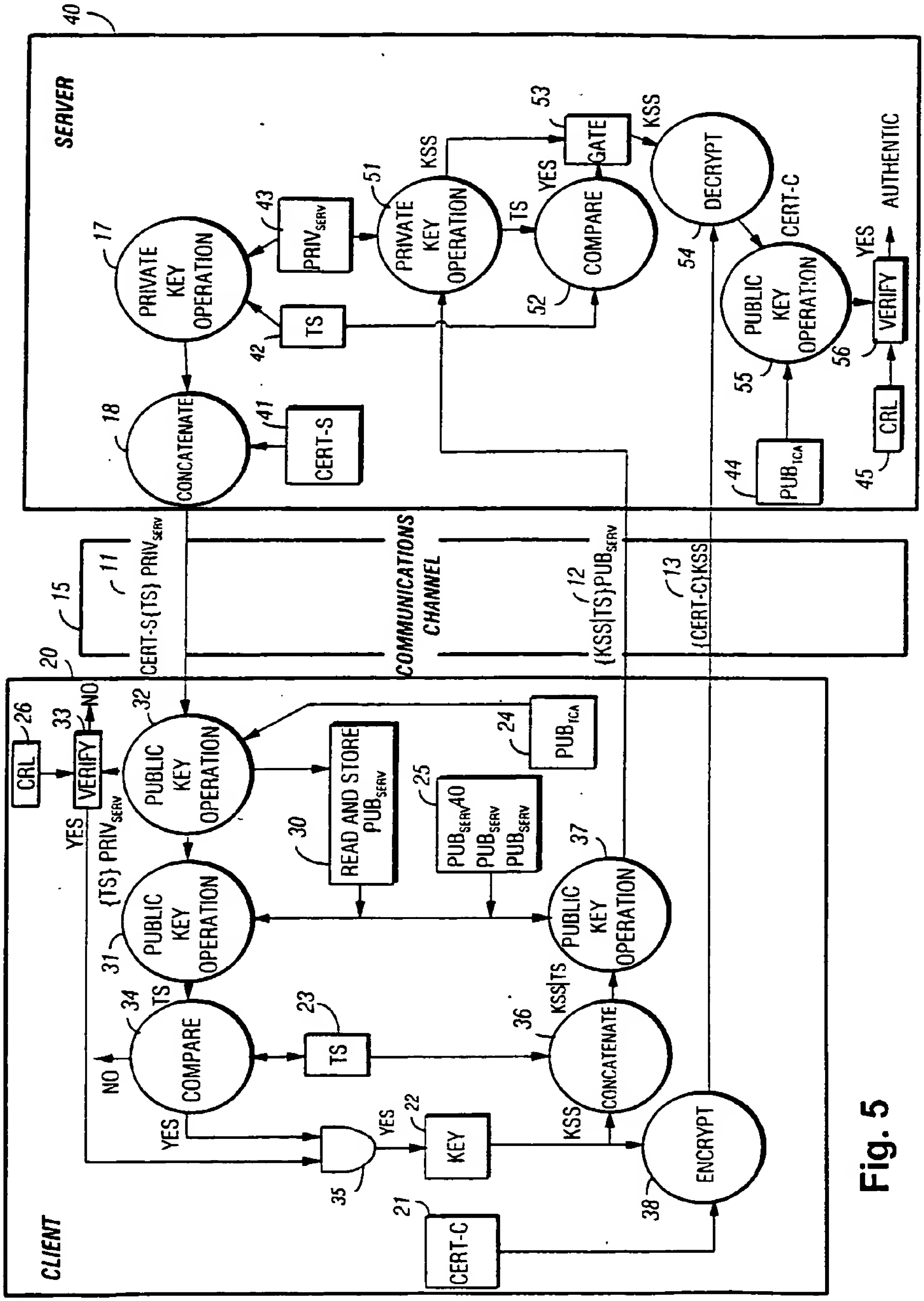

SERVER
40
PRIVATE KEY OPERATION
17
CONCATENATE
18
CERT-S
41
TS
42
PRIV$_{SERV}$
43
PRIVATE KEY OPERATION
51
KSS
COMPARE
52
YES
GATE
53
DECRYPT
54
CERT-C
PUBLIC KEY OPERATION
55
VERIFY
56
YES
AUTHENTIC
CRL
45
PUB$_{TCA}$
44
COMMUNICATIONS CHANNEL
15
11
CERT-S{TS} PRIV$_{SERV}$
12
{KSS|TS}PUB$_{SERV}$
13
{CERT-C}KSS
CLIENT
20
CRL
26
VERIFY
33
NO
PUBLIC KEY OPERATION
32
YES
{TS} PRIV$_{SERV}$
READ AND STORE PUB$_{SERV}$
30
PUB$_{TCA}$
24
PUB$_{SERV}$40
PUB$_{SERV}$
PUB$_{SERV}$
25
PUBLIC KEY OPERATION
31
PUBLIC KEY OPERATION
37
COMPARE
34
TS
NO
TS
23
CONCATENATE
36
KSS|TS
YES
35
YES
KEY
22
KSS
ENCRYPT
38
CERT-C
21

Fig. 5

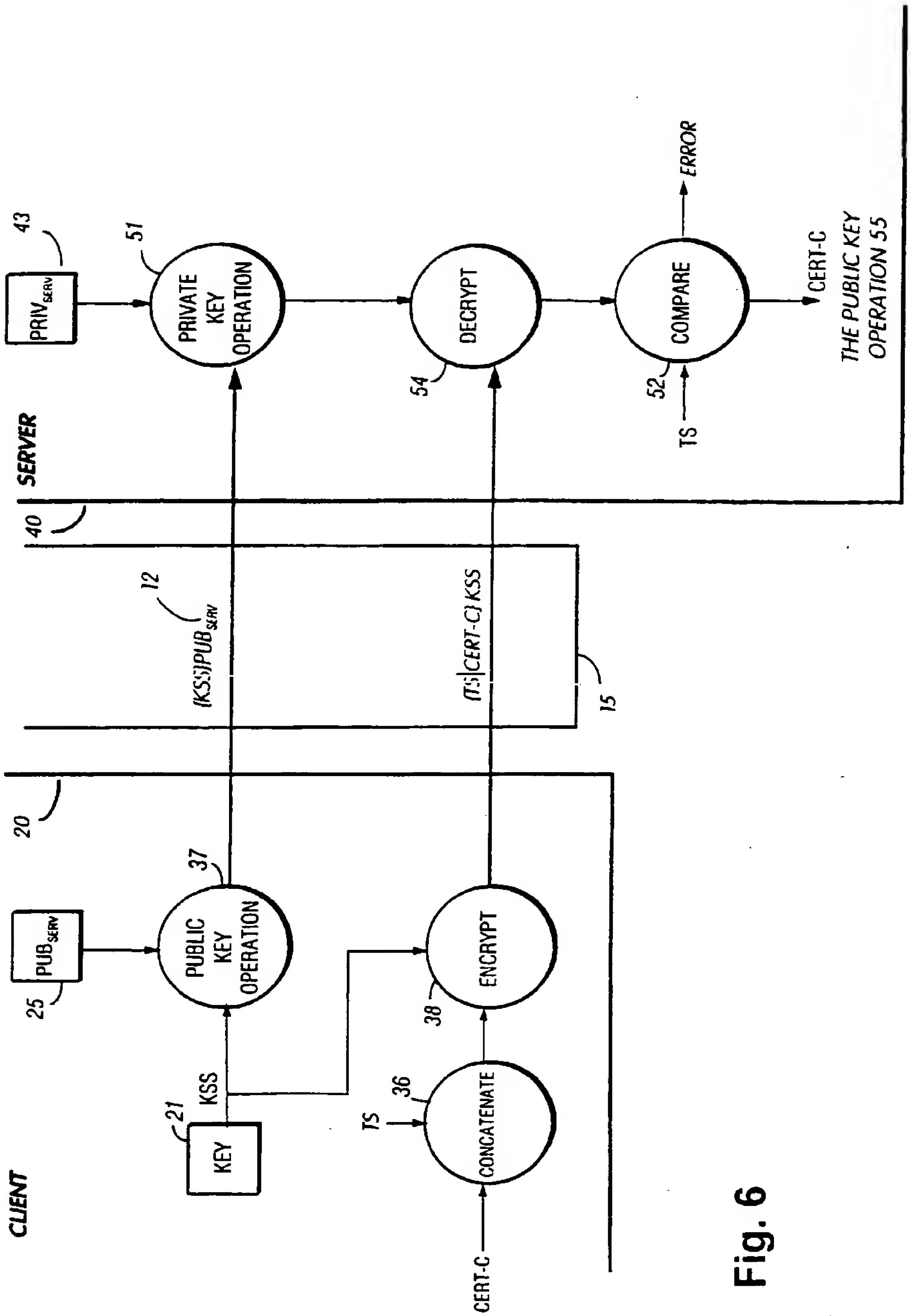
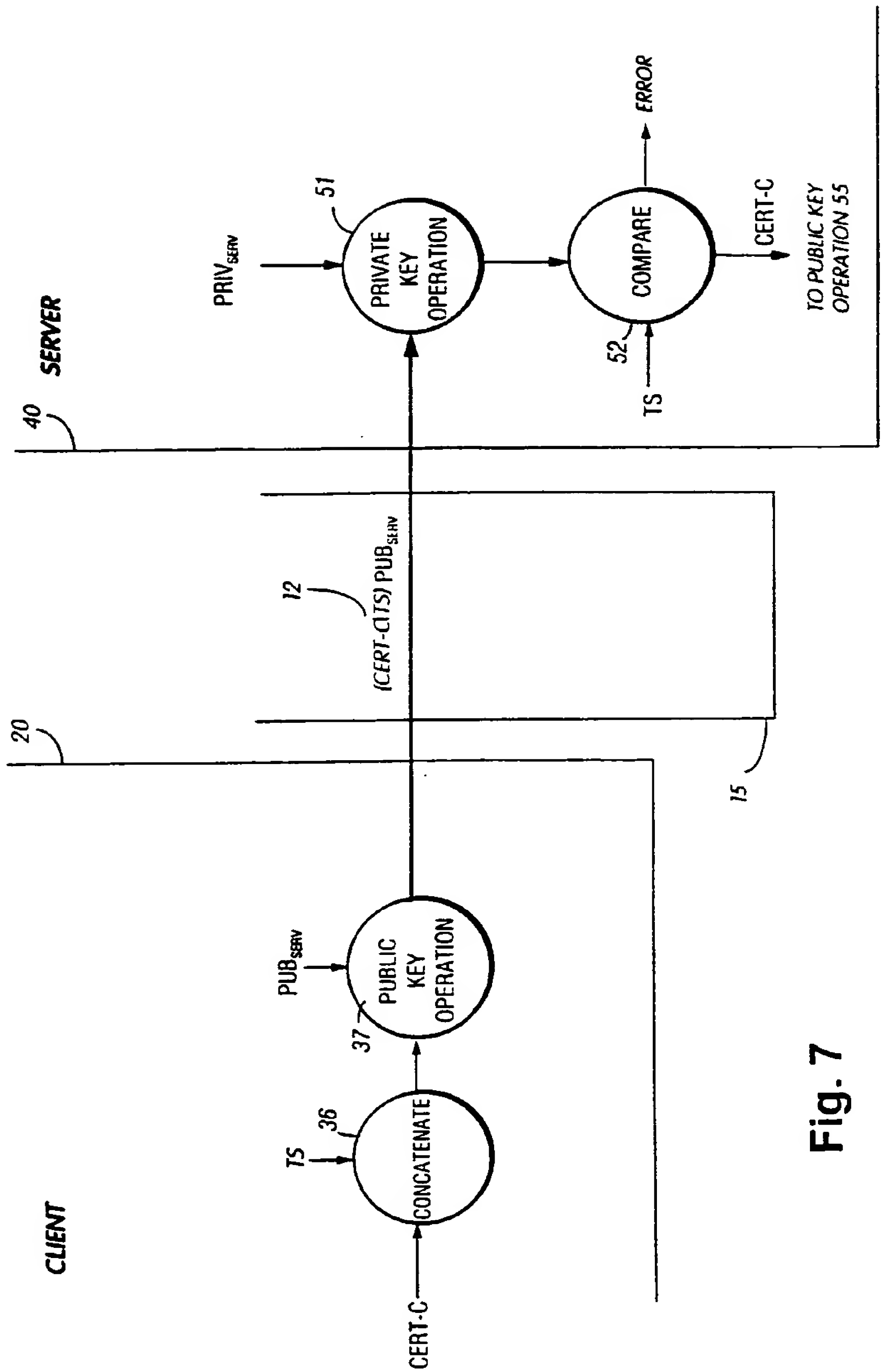

CLIENT
SERVER
KEY
21
KSS
PUB_SERV
25
PUBLIC KEY OPERATION
37
20
CONCATENATE
36
TS
CERT-C
ENCRYPT
38
{KSS}PUB_SERV
12
{TS|CERT-C} KSS
15
40
PRIV_SERV
43
PRIVATE KEY OPERATION
51
DECRYPT
54
COMPARE
52
TS
ERROR
CERT-C
THE PUBLIC KEY OPERATION 55

Fig. 6



CLIENT
SERVER
CERT-C
TS
36
CONCATENATE
37
PUB$_{SERV}$
PUBLIC KEY OPERATION
20
15
12
(CERT-C|TS) PUB$_{SERV}$
40
PRIV$_{SERV}$
51
PRIVATE KEY OPERATION
52
TS
COMPARE
ERROR
CERT-C
TO PUBLIC KEY OPERATION 55

Fig. 7

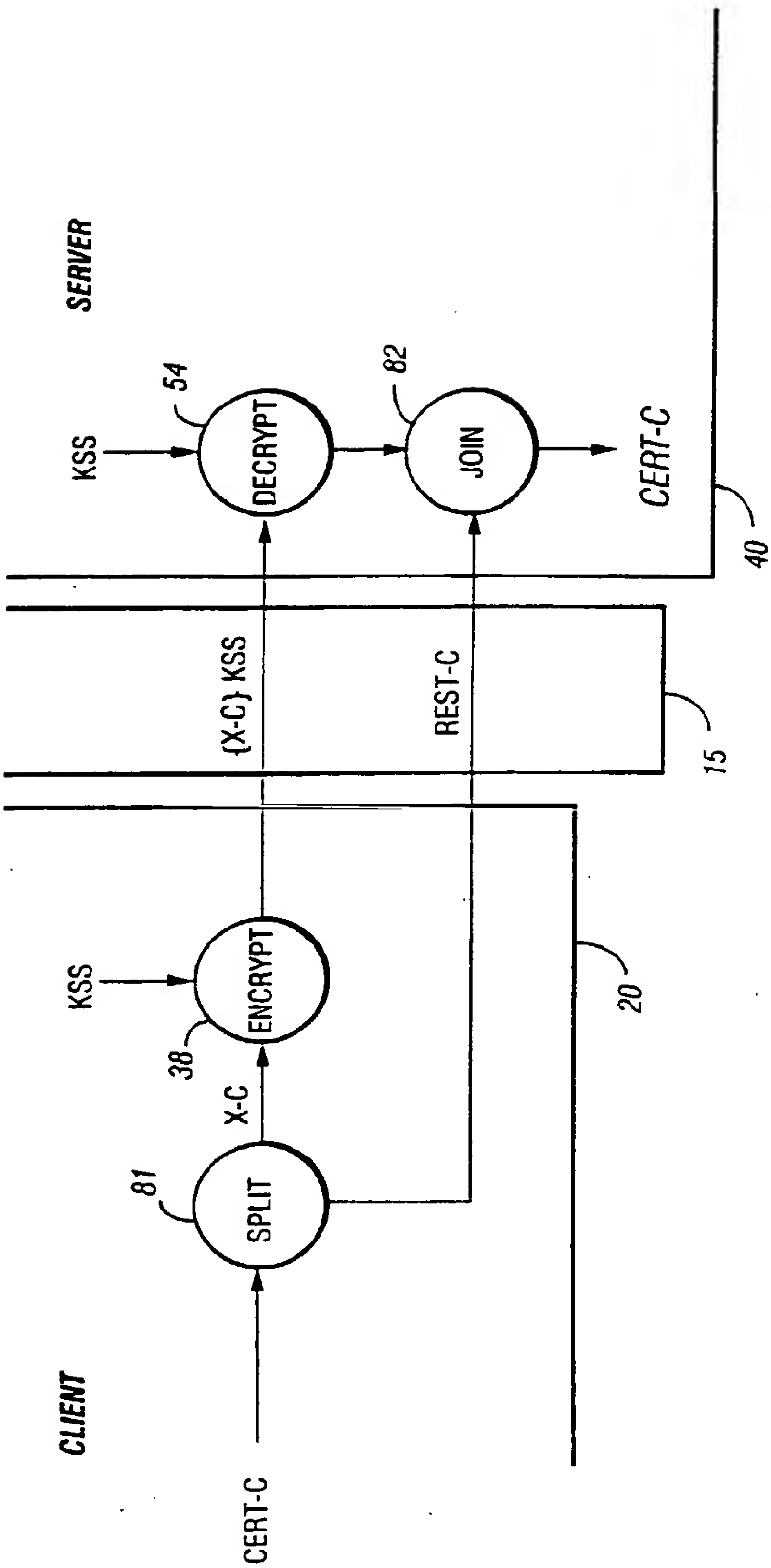

CLIENT
SERVER
CERT-C
SPLIT
81
X-C
ENCRYPT
38
KSS
{X-C} KSS
REST-C
KSS
DECRYPT
54
JOIN
82
CERT-C
20
15
40

Fig. 8

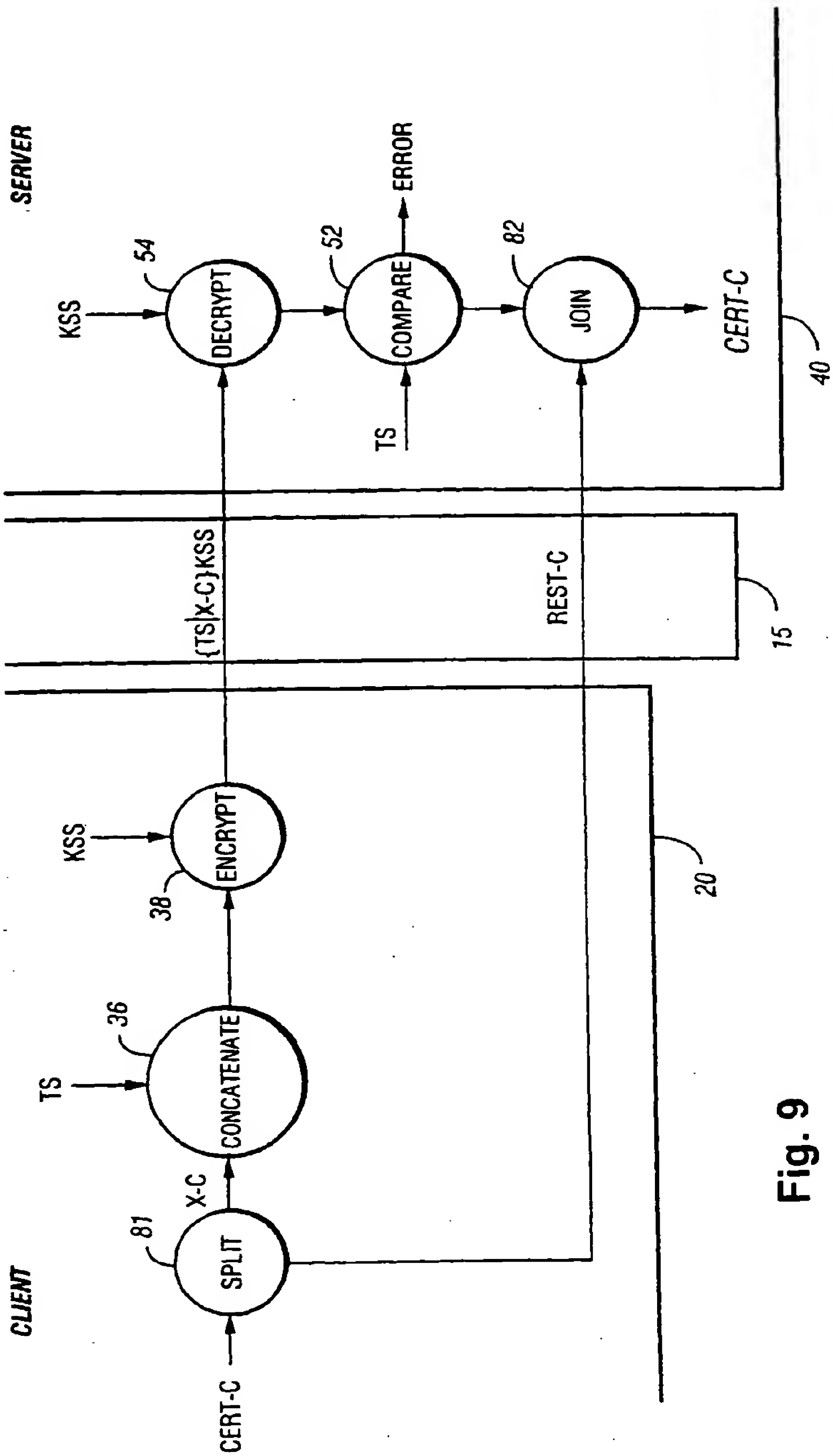

CLIENT
SERVER
CERT-C
SPLIT
81
X-C
TS
CONCATENATE
36
KSS
ENCRYPT
38
{TS|X-C}KSS
REST-C
KSS
DECRYPT
54
TS
COMPARE
52
ERROR
JOIN
82
CERT-C
15
20
40

Fig. 9

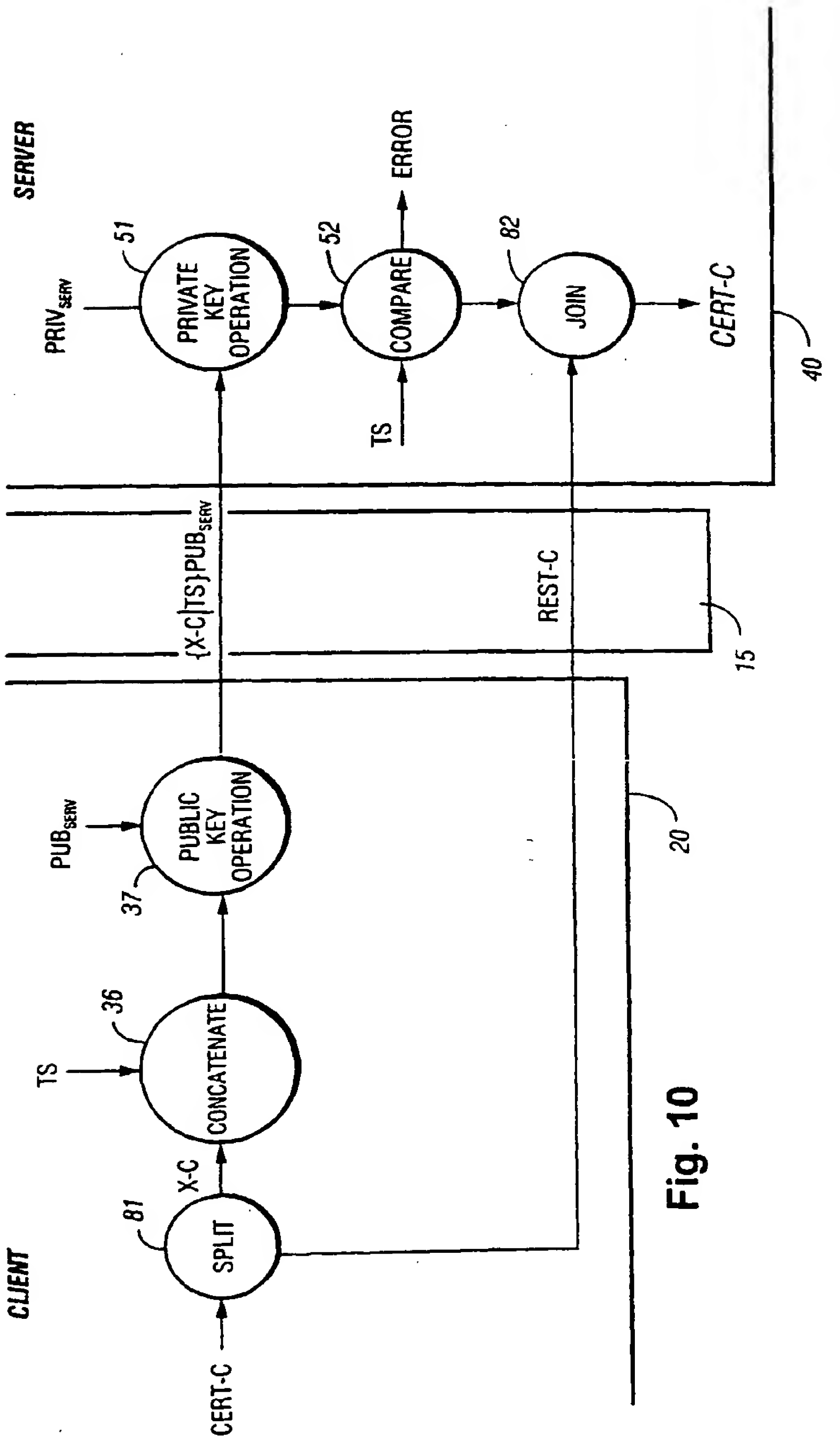

CLIENT
SERVER
CERT-C
SPLIT
81
X-C
TS
CONCATENATE
36
PUB$_{SERV}$
PUBLIC KEY OPERATION
37
{X-C|TS}PUB$_{SERV}$
REST-C
15
20
PRIV$_{SERV}$
PRIVATE KEY OPERATION
51
COMPARE
52
ERROR
TS
JOIN
82
CERT-C
40

Fig. 10

Fig. 11

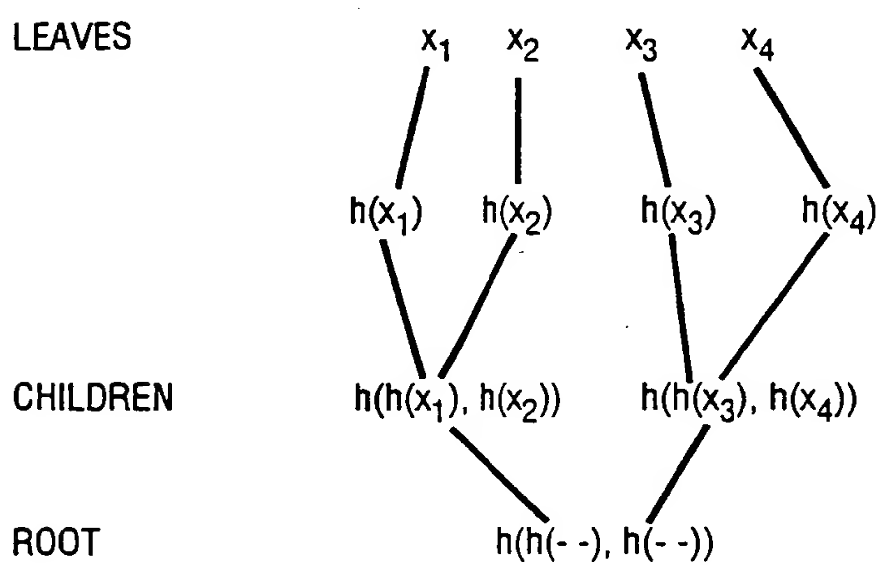
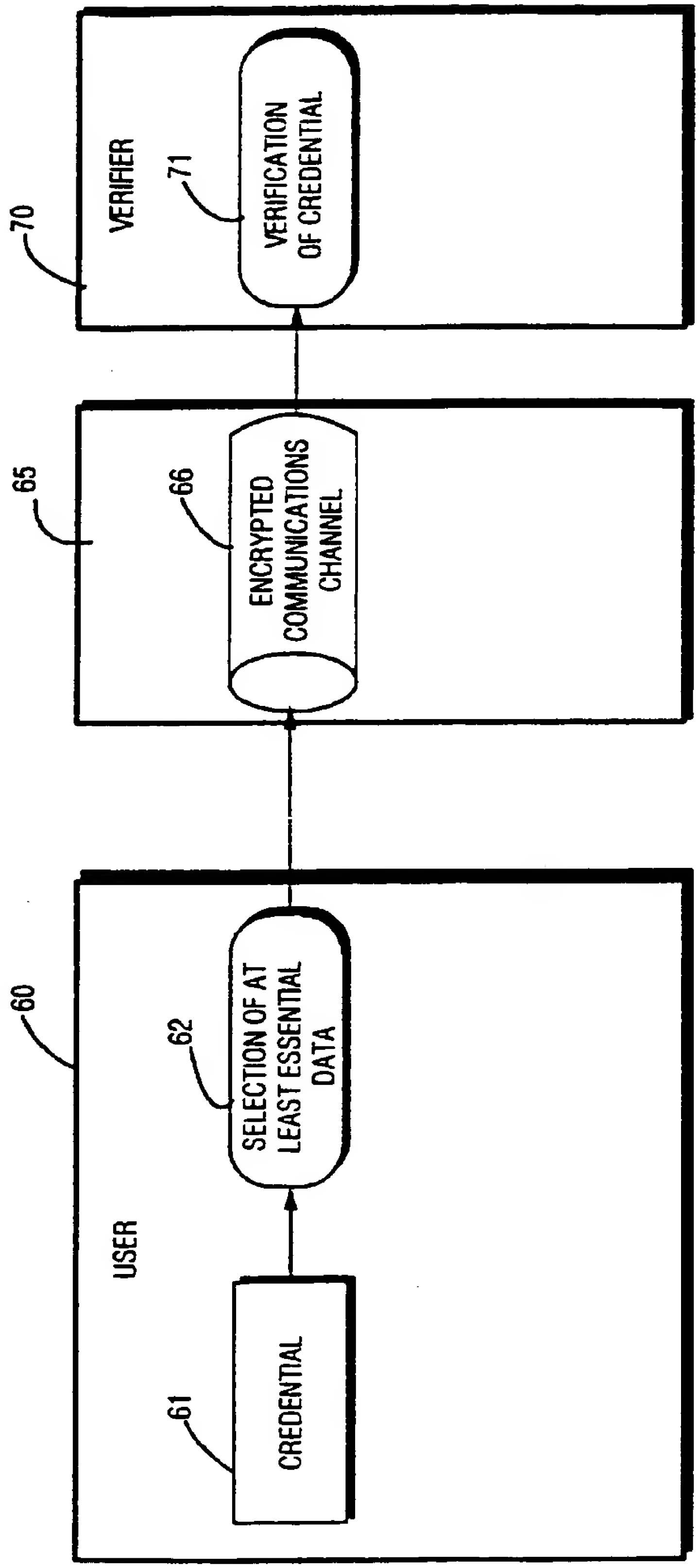

LEAVES
x_1 x_2 x_3 x_4
$h(x_1)$ $h(x_2)$ $h(x_3)$ $h(x_4)$
CHILDREN
$h(h(x_1), h(x_2))$ $h(h(x_3), h(x_4))$
ROOT
$h(h(- -), h(- -))$

Fig. 12


60
USER
61
CREDENTIAL
62
SELECTION OF AT LEAST ESSENTIAL DATA
65
66
ENCRYPTED COMMUNICATIONS CHANNEL
70
VERIFIER
71
VERIFICATION OF CREDENTIAL